Government of Saint Lucia

Ministry of Infrastructure, Port Services and Transport

Hurricane Tomas Emergency Recovery Project

Hydraulic assessment for flood risk assessment in Soufrière, Fond St Jacques and Dennery

Report # 2: Drainage Designs Standards and Flood Risk Mapping

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Acronyms and abbreviations

DRM	Disaster Risk Management
GOSL	Government Of Saint Lucia
PCU - MF	Project Coordination Unit – Ministry of Finance
MIPS&T	Ministry of Infrastructure, Port Services and Transportation
MOSSAIC	Management of slope stability in communities
NRDU	National Reconstruction and Development Unit

Chapter 1. Introduction

The vulnerability of Saint Lucia's population and economy, to natural disasters related to water phenomena has become an important national issue.

In October 2010, the Hurricane Tomas impacted Saint Lucia. An important rainfall, in quantity (533 mm) and duration (24 hours), accompanied this hurricane. Due to Saint Lucia's topography and land occupation, numerous flooding and landslide were deplored. To support the Saint Lucia's recovery and reconstruction effort the government of the island received a Credit from the World Bank.

The extreme rainfall associated to the Hurricane Tomas also altered the river-courses and accumulated sediment in the channels due to significant number of landslides and important run-off. Theses sediments now increase the flooding risk, in particular on specific risk areas: the watershed communities of Dennery, Soufriere and Fond St-Jacques.

The objectives of the assignments are to provide the implementation of flood management measures in 3 watershed areas (of the Dennery, Soufriere and Fond St-Jacques communities):

- Carry out flood risk assessment
- Identify and quantify appropriate cost effective remedial measures to reduce flood hazard.

The project is divided in 6 phases:

- Phase 1 : Site characterization, flood hazard and vulnerability analysis
- Phase 2 : Drainage designs standards and flood risk mapping
- Phase 3 : River and drainage and mitigation measures
- Phase 4 : Preliminary designs
- Phase 5 : flood mitigation measures
- Phase 6 : Flood risk design and flood management training

This report describes the phase 2 analysis. It contains:

- The drainage design standards
- The hydrological analysis
- The topographical survey
- The hydraulic modeling
- The flood exposure maps of the 3 communities

Figure 1 : Location Map : Dennery, Fond Saint Jacques and Soufrière

Chapter 2. Drainage design standards

2.1 General points

2.1.1 Disaster risk profile of Saint Lucia and focus on the studied areas

Saint Lucia is located in the Eastern Caribbean in the Windward Island chain at 13o 53' N latitude and 60o 58' W longitude.

Bordered to the north by Martinique and to the south by St. Vincent and the Grenadines, Saint Lucia supports a population of approximately 170,000. The island of Saint Lucia occupies approximately 616 km2 with a length of approximately 50 km on the north-south axis and 25 km along the east-west axis. The island is mountainous of volcanic origin, with its highest peak, Mt. Gimme, rising some 950 meters above sea level.

Saint Lucia is located in the Atlantic hurricane belt, and while infrequent, the island is exposed to potentially serious storm impacts. Notable storms include Hurricane Allen, 1980; Tropical Storm (later Hurricane) Debby, 1994; Tomas in 2010 and the last tropical storm at Christmas Eve 2013.

Saint Lucia experiences landslides, particularly in the aftermath of heavy rains. Additionally, the island periodically experiences earthquakes of generally lower magnitudes. The island is classified as seismic zone 2 on a 4-class scale, indicating low to moderate earthquake risk.

Finally, storm surge and flash flood are among the other risks regularly faced by the island.

Floods and Landslides

The principal flood threat in Saint Lucia is from storm surge and coastal wave action. Particularly at risk are low-lying coastal areas such as the town of Dennery and the area of Anse La Raye which have experienced significant flooding in the past.

Flash flooding in the interior presents a risk to local inhabitants along streams and coastal erosion due to wave action can threaten adjacent tourism activities.

Saint Lucia's mountainous topography coupled with its volcanic geology produces a significant opportunity for landslides. Much of the island's housing is distributed along steep slopes and poorly engineered and constructed housing is particularly at risk. Loss of watershed integrity, particularly on slopes above inhabited areas serves to destabilize slopes and increase risks for property losses. This risk is increased during the annual rainy season (May-November) and during the passage of tropical depressions and hurricanes from July to November.

To conclude, the studies areas of Soufriere Town and Dennery are situated along a river and in a coastal area. They are threatened by both flash floods and coastal submersion risks.

Fond Saint Jacques is situated in the mountains, along a ravine and surrounded by steep slopes. The landslide risk associated with flash floods risk cause devastating mudflows and debris flows in the area.

2.1.2 Vulnerability in Saint Lucia

Poorly regulated construction and land use practices are among the biggest contributors to risk from losses in Saint Lucia. Lack of uniform enforcement of building codes contributes to the vulnerability of island infrastructure.

Due to the steep topography of the island, land use is a major factor in determining vulnerability to adverse events. Loss of vegetation, particularly in upper watersheds, has resulted in increased runoff potential and slope destabilization.

In Fond Saint Jacques, poor drainage management associated with small interior communities promotes soil saturation and subsequent landslip. Informal settlements are located where landslip risk is greatest. This community is least likely to have access to significant engineering support. The lack of legal title (land ownership/tenure) has led to unsustainable land use and poor land conservation practices which results in soil erosion and land slippages.

Other environmental aspects such as deforestation and soil erosion, might be a result of the impact of natural hazards and may impact Saint Lucia’s vulnerability.

Towns in Saint Lucia built in relatively flat stream valleys adjacent to the coast, such as Dennery and Soufriere are the areas most susceptible to storm surge and flooding. This risk has increased over years with loss of upper watershed through its conversion to agricultural use. Increased rainfall runoff has increased coastal flood potential. In those towns, the lack of legal title (land ownership/tenure) has led to unsustainable land use and poor land conservation practices which results in silting of rivers and coastal waters.

2.1.3 Disaster Risk Management framework

Disaster preparedness and response activities are vested with the National Emergency Management Organization (NEMO) in conformance with the responsibilities and authorities assigned in the Disaster Management Act of 2006. These include Disaster management/response, disaster planning, and risk assessment and mitigation activities. Saint Lucia is a signatory to the Caribbean Disaster Emergency Response Agency Agreement which provides regional support to Saint Lucia in the event of a major disaster.

Saint Lucia's revised Disaster Management Plan has been formally adopted (2007). Under this plan, disaster coordination is focused on the offices of NEMO which is charged with planning, mitigation, and response functions. NEMO operates under the direction of the Prime Minister who chairs NEMAC, the National Emergency Management Advisory Committee. This committee is composed of the Permanent Secretaries of the various Saint Lucian Ministries, as well as chairs of the national committees and heads of key agencies such as police, fire, Red Cross, ports authority and others.

Fifteen national disaster committees have been established with a focus on their respective sectors such as telecommunications, shelters, works, health, transport and others. These committees work with NEMO to provide specialized expertise in their respective sectors. Additionally, community-based response and planning is represented by eighteen District committees which cover the country.

The National Emergency Management Plan includes numerous plans and policy documents to guide prevention, mitigation and response.

These documents guide disaster mitigation and management by assigning specific responsibilities and procedures under a policy framework for disaster risk management and reduction. Documents supporting the national plan include Standard Operating Procedures (SOPs), policy documents, guideline documents, national emergency plans, sectoral/agency response plans, and a number of agreements. The Governor-General may, by proclamation which is then published in the Official Gazette, declare that a state of emergency exists.

2.1.4 Disaster legislation

Saint Lucia has enacted a significant disaster legislation and is signatory to a number of regional and international conventions for disaster management. **The country has developed and approved a number of policies, plans and standard operating procedures relevant to disaster risk reduction. These include:**

- **The Emergency Powers (Disasters) Act #5, 1995**
- **The Disaster Preparedness and Response Act, 2000**
- **The Disaster Management Act # 30, 2006**
- **Mitigation Policy & Plan**
- **Integrated Natural Hazard Risk Management Policy 2004 (draft)**
- **Landslide response plan, 2006**

NEMO leads the disaster management initiative with the support and the participation of most agencies in all sectors. However, a coherent national multi-sectoral plan is yet to be developed. NEMO is working with other national ministries and agencies to systematically integrate DRM within specific agency activities and what currently exists is not as systematic as it could be. However, NEMO provides DRM elucidation to the activities, programs and projects of a number of public and private sector agencies including the Climate Change Unit, the Sustainable Development Unit, the Ministries of Physical Development, Agriculture, Fisheries, etc.

While much progress has been made, DRM policy implementation advancements at the national level are impeded by staffing and funding constraints. Additionally, individual Ministries have yet to fully integrate DRM principles in the management of their respective portfolios.

2.1.5 The landslide response plan

This plan was developed by NEMO in 2006.

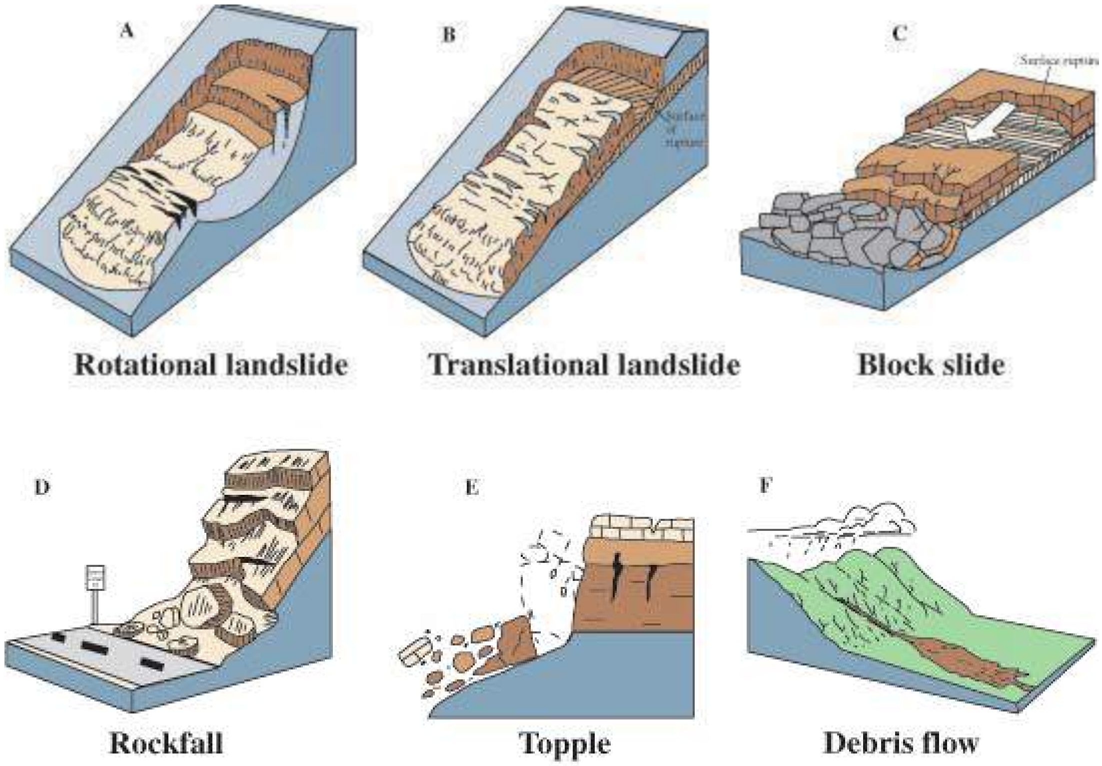
WHAT IS A LANDSLIDE?

It is a down slope transport of soil and rock resulting from naturally occurring vibrations, changes in direct water content, removal of lateral support, loading with weight, and weathering or human manipulation of water course and slope composition.

LANDSLIDE TYPES :

- Rotational
- Translational
- Debris flow
- Debris avalanche

Figure 2 : Landslide types



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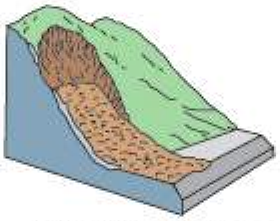

Debris avalanche

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Earthflow

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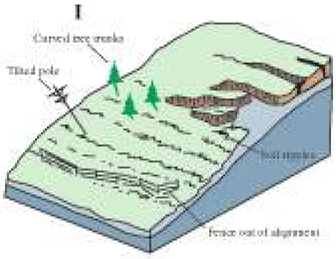
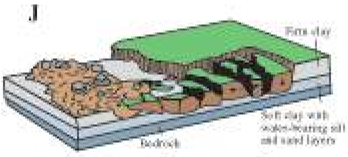


Creep

J



Lateral spread

CHARACTERISTICS

Landslides vary in types of movement (falls, slides, topples, lateral spread, flows) and may be secondary effects of heavy storms, earthquakes, and volcanic eruptions. Landslides are more widespread than any other geological event.

LIKELY IMPACT -> Physical Damage :

- Anything on top of or in the path of a Landslide will suffer damage
- Rubble may block roads, lines of communication or waterways. Indirect effect may include loss of productivity of agricultural or forest lands.
- Flooding.
- Reduced property values, destruction of buildings.
- Casualties- fatalities may occur due to slope failure.

FACTORS CONTRIBUTING TO VULNERABILITY

- Settlements built on steep slopes, softer soils and cliff tops
- Settlements built at the base of steep slopes, on mouths of streams from mountain valleys.
- Roads, communication lines in mountain areas
- Buildings with weak foundations
- Buried Pipelines and brittle pipes.
- Lack of understanding of landslide hazard

PREPAREDNESS MEASURES

Community Education after identification of areas most at risk from landslides. The basic information required:

- Knowledge of where past Landslides have occurred derived from local records and knowledge of certain types of rocks prone to landslides.
- Monitoring, warning and evacuation systems

MITIGATION MEASURES

- Capture and drainage of water before it reaches potential slope area
- Underground drainage by using sub-surface pipes
- Land Reform by terracing/re-shaping

TYPICAL POST-DISASTER NEEDS

- Search and rescue (use of earth removal equipment)
- Medical assistance
- Emergency shelter for homeless.

LEGISLATION

Legislation is an effective tool for the implementation of Landslide management activities.

In some cases specific legislation concerning Landslides is enacted. In other cases, Landslide

management and Landslide response activities have legal support from several different legislation.

The landslide risk, landslides inventory and debris risk maps of Saint Lucia are shown next pages (2006).

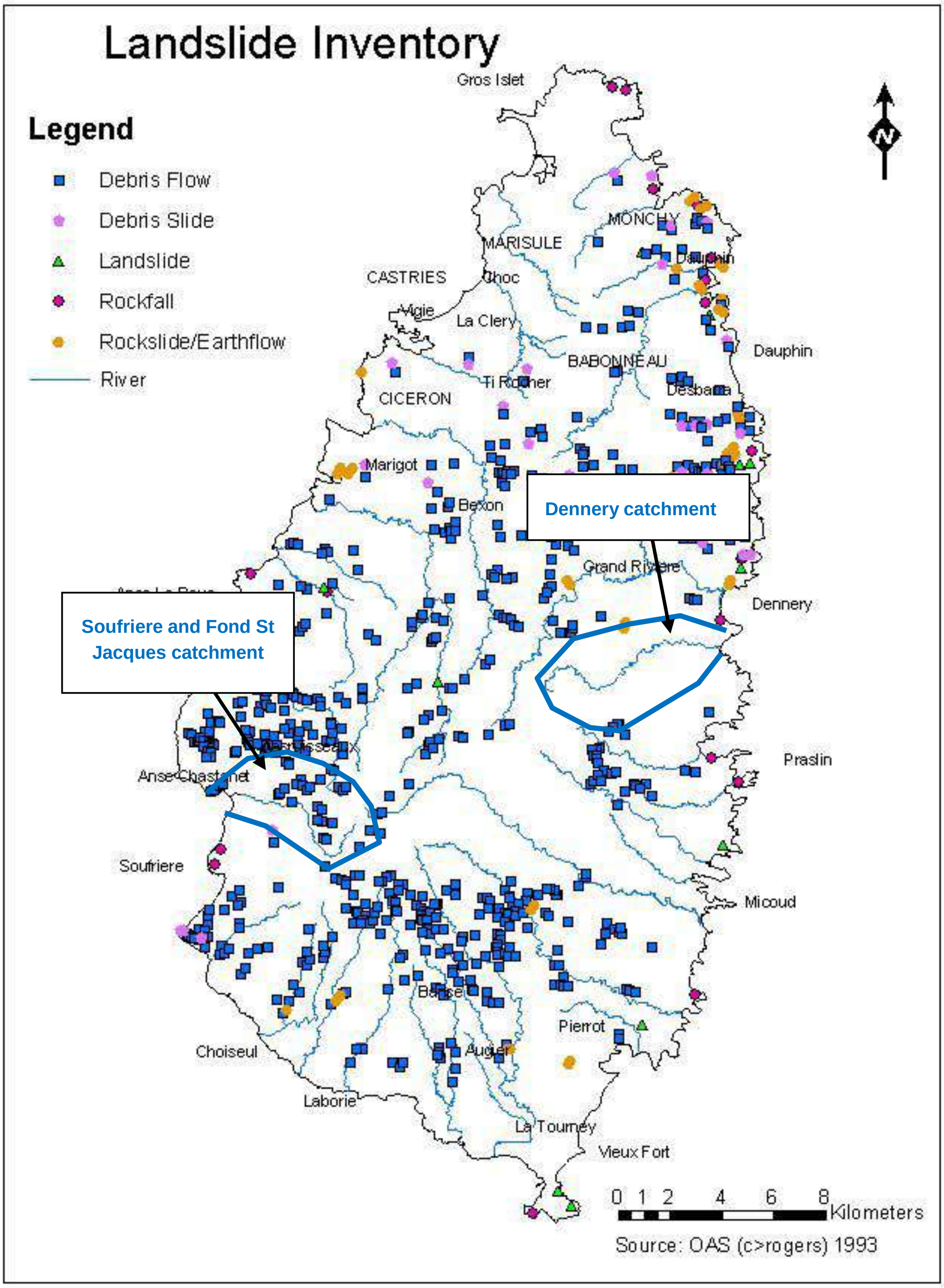
The risk map shows that the upstream side of the Soufriere catchment has extreme and high risk of landslides, especially in Fond Saint Jacques.

The towns of Soufriere and Dennery have low risk of landslides.

The center of the island is uncovered by geological studies: no bedrock mapping is available, especially in the upstream catchment of Fond saint Jacques and Dennery.

The inventory of landslides and debris risk show a lot of “debris flow” landslides type, in particular around Fond Saint Jacques. Fond Saint Jacques has an extreme risk of debris flow.

Figure 3 : Landslide inventory – NEMO 2006

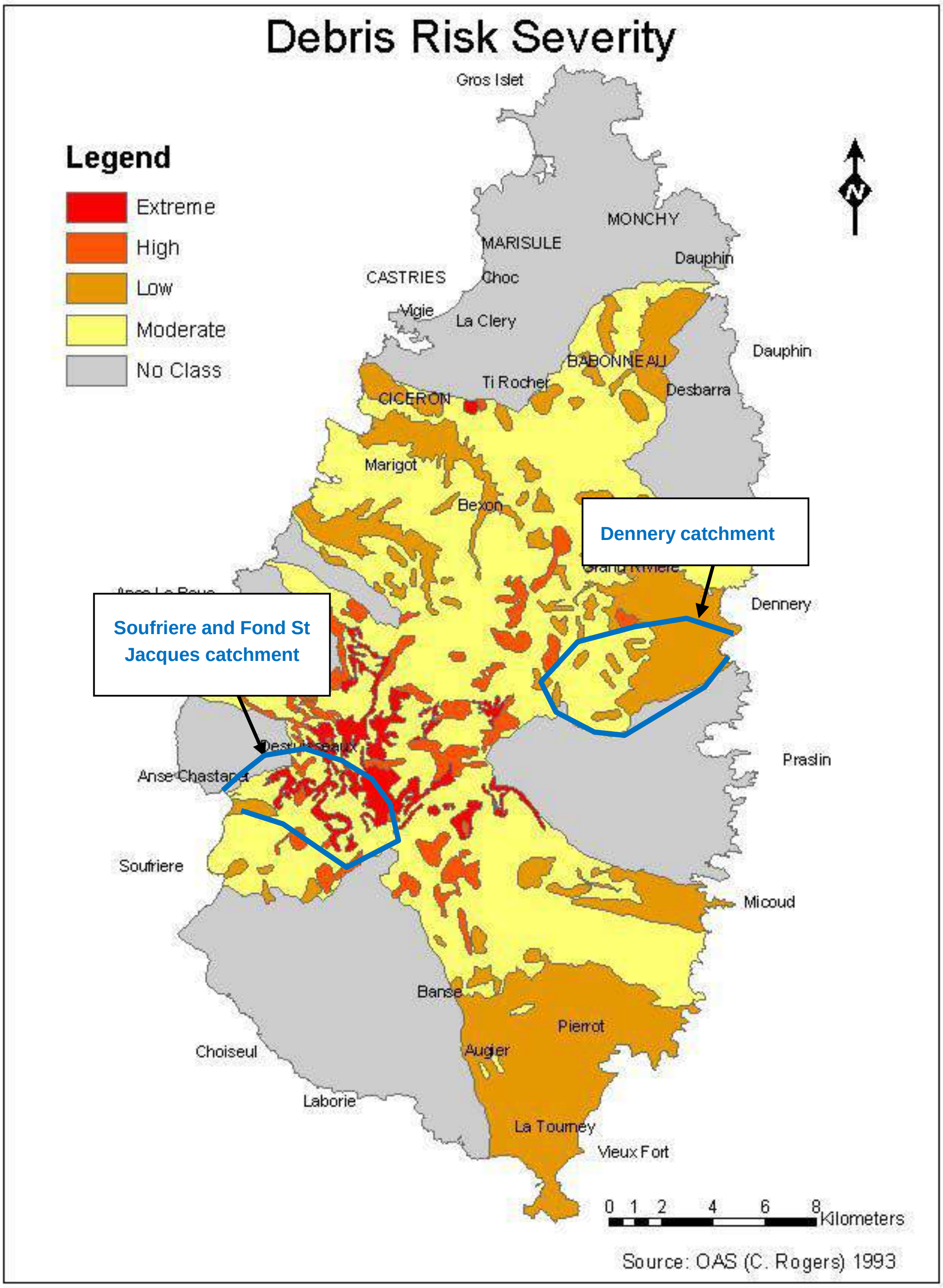


Dennery catchment

Soufriere and Fond St Jacques catchment

Source: OAS (c>rogers) 1993

Figure 4 : Debris Risk Severity – NEMO 2006



Dennery catchment

Soufriere and Fond St Jacques catchment

Source: OAS (C. Rogers) 1993

2.1.6 Climate change

Climate change is likely to have implications for today's urban flood risk management decisions, but is one of many drivers that must be considered (e.g. urbanization, aging infrastructure, and population growth).
Failure to adequately treat climate change in decision making today could lead to future unnecessary costs, wasted investments and risks to life. Decision makers therefore require long term projections of risk, as well as detailed hazard maps of current flood risk. The idea that climate change will cause huge changes in risk and therefore render current flood risk management practice obsolete in the future is widespread and justified in some cases. This makes it highly problematic for governments and individuals to make confident decisions and to critically assess their investments in risk management. Long-term infrastructure is an area where planning decisions are likely to be sensitive to assumptions about future climate conditions. It is, therefore, crucially important to explore the implications of climate change for future flood hazard and to look for ways to build those implications into decision making processes.

There exists a broad consensus that flood risk is already changing at a significant rate, and that the rate of change might intensify in the next coming decades. A variety of climatic and non-climatic variables influence flood processes. Some of the climatic variables that flood magnitudes depend upon are precipitation intensity, timing, duration, phase (rain or snow) and spatial distribution.

Saint Lucia's population and infrastructure is increasingly at risk to some of the possible negative impacts of climate change. There is potential for increased flood risk from:

- Increased precipitation
- Drought leading to land subsidence
- Rising sea levels

Dennery and Soufriere urban centers located in low-lying coastal areas are particularly vulnerable to sea level rise, storm surge and heat waves, all of which are likely to worsen due to climate change. According to the last IPCC report, published in 2013, the mean sea level due to global warming is forecasted to rise between 0.26 m and 0.82 m from now to 2100.

Estimation of impacts of sea level rise, increasing temperatures and changing rainfall patterns, and the development of robust adaptation pathways, is complicated by a combination of the characteristics of the infrastructure to be protected and the uncertainty of local and regional climate projections.

Projections of extreme events in the tropics are uncertain, due in part to the difficulty in projecting the distribution of tropical cyclones using current climate models with too coarse a spatial resolution, but also due to the large uncertainties in observational cyclone datasets for the 20th Century.

2.2 Drainage design standards

2.2.1 Drainage standards in St Lucia

2.2.1.1 Drainage design

Drainage systems and structures in St Lucia are generally designed for rainfall events having return periods of 20 years.

This means that such systems are likely to become overloaded and cause some degree of flooding when rainstorms are experienced with return periods greater than 20 years.

But no official requirements were found relating to torrential rains drainage design.

2.2.1.2 The Management of Slope Stability in Communities [MoSSaiC] :

In 2004, an academic team from the University of Bristol came up with a way to address this problem: Management of Slope Stability in Communities (MoSSaiC). Its work started in a number of communities with the support of the Government of Saint Lucia, and later continued in partnership with several international organizations, and particularly the World Bank, through the Saint Lucia Second Disaster Management Project. The approach centers its vision on sustainable foundations for community-based landslide risk reduction, rooted in science, communities, and evidence.

The scientific foundations of MoSSaiC focus on the identification of localized physical causes of landslide risk (such as poor drainage), the identification of appropriate mitigation measures to address these causes (such as constructing drains), the justification of these solutions to both the community and the government, and the explanation of the need for a certain standard and quality of design and construction, so that the root cause of the hazard is effectively addressed.

What sets MoSSaiC apart from many other interventions is that it is rooted in communities from start to finish. Community residents are engaged in identifying landslide risk causes and solutions, employed in constructing the drainage solutions, and they work together with government managers and practitioners to deliver the mitigation measures. As a result, the vision for this proactive, sustainable approach to slope management is shared, championed, and owned by the communities themselves, not only by the government or an implementing agency.

The evidence-based piece of MoSSaiC continues to grow over time. The majority of project funding and time is spent directly in the communities, and due to the high levels of local engagement, both behavior and policy are gradually changed. Now that MoSSaiC has been implemented in a dozen communities, we can also safely say that the investments of resources and effort have definitely paid off: In October 2010, Hurricane Tomas (a 1-in-500-year 24-hour rainfall event) caused numerous landslides all across Saint Lucia. However, none of the vulnerable communities with MoSSaiC interventions experienced any landslides at all, despite the fact that they frequently used to be affected by substantially weaker events in the past. To date, 261 homes have benefitted from the Second Disaster Management Project MoSSaiC interventions.

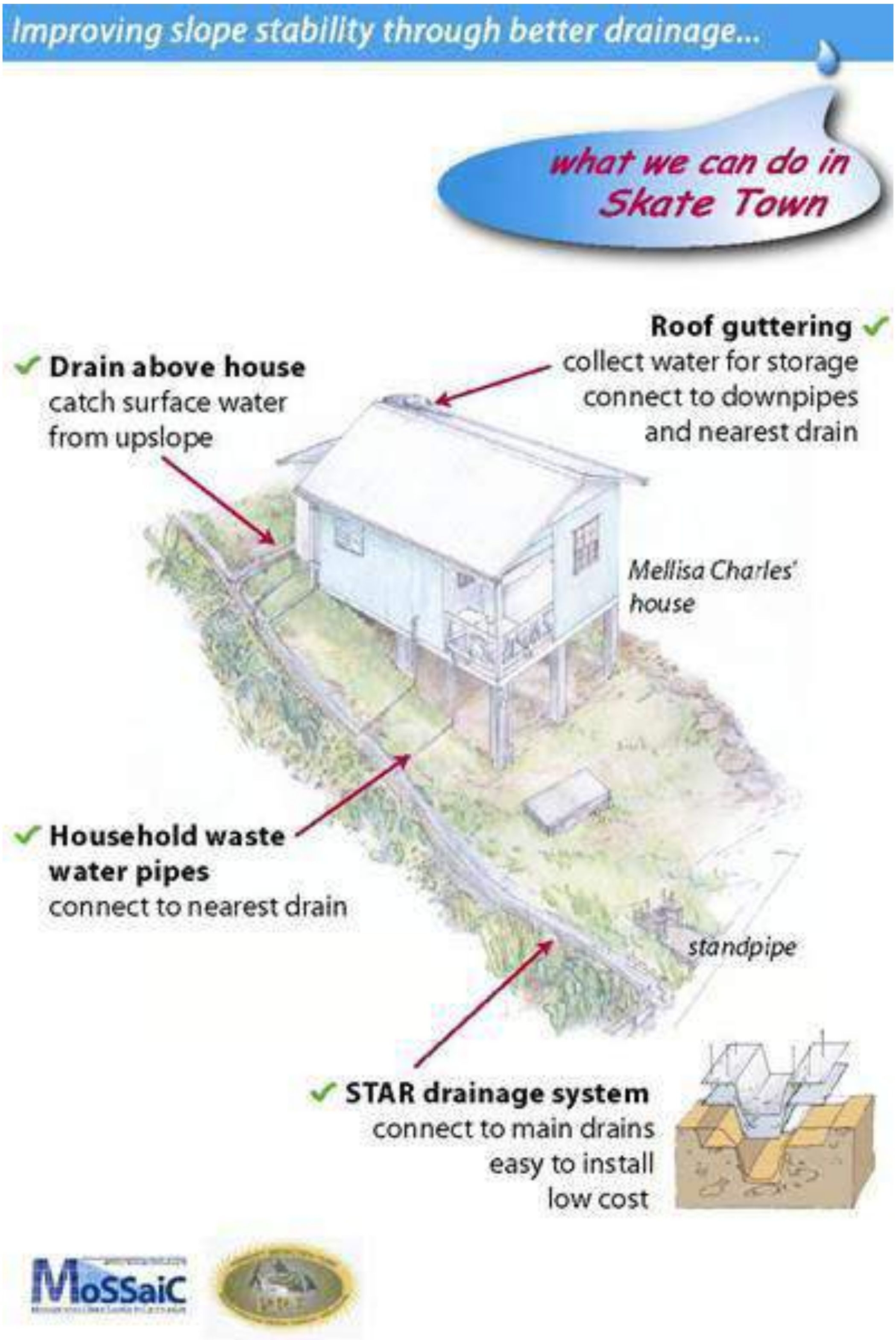


Figure 5 : MOSSAIC drainage design standards

2.2.1.3 Checklist and Fees for the submission of planning Applications

This note, developed by the Ministry of Physical Development and the Environment in 2006, is given for developers.

It specifies that permission must be obtained from the Development Control Authority before carrying out any type of Development on Land.

For land subdivision, a plan must indicate all existing structures, natural features including water courses and requisite buffers to the watercourse. (see illustration below).

But it is only principles. No return period for drainage design standards is given.

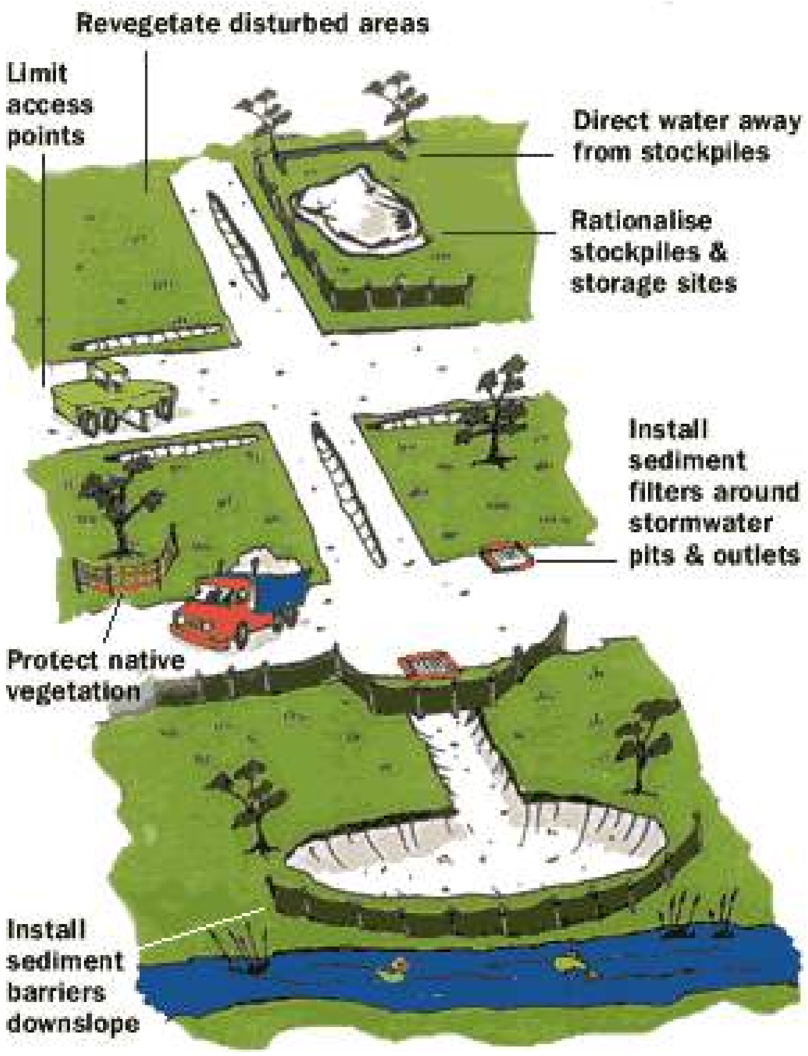


Figure 6 : Land subdivision drainage design principles

2.2.2 Interreg program

The INTERREG IV "Caribbean" program was approved by the European Commission on 27 March 2008, for the benefit of the regions of Guadeloupe, French Guiana, Martinique and the Overseas collectivity (COM) of Saint-Martin.

This program is part of the cohesion policy of the European Union and comes under the "European territorial cooperation" 2007/2013 aimed at strengthening:

- strengthen cooperation across borders by joint local and regional initiatives,
- strengthening transnational cooperation by means of actions conducive to integrated link with the priorities of the Community regional development,
- strengthening interregional cooperation and exchange of experience at the appropriate territorial level.

As such, *INTERREG IV "Caribbean"* has a budget of approximately 64 million Euros, 75% from the European Regional Development Fund (ERDF).

The balance (25%) is co-financed by the regions of Guadeloupe, Guyana, Martinique, Overseas collectivity (COM) of Saint-Barthélemy and Saint-Martin, by the state and by private self-financing. The managing authority of the program is the Regional Council of Guadeloupe, assisted by the Joint Technical Secretariat (JTS) in charge of communication, entertainment, education as well as financial and administrative monitoring of the program with support, Regional Contact Points (PCR) located on the cooperation area.

The area cooperation program covers almost all countries with a coastline with the Caribbean Sea, including saint Lucia.

Figure 7 : INTERREG Caribbean Program area

The thematic priorities of Interreg IV Caribbean program are grouped into 3 axes.

One of these axes is “Prevention Natural and Sustainable Development Management » :

Enhance and protect the environmental assets across the common and sustainable management of land, water resources, etc., and risk prevention.

- Actions to promote the conservation, management and sustainable and coordinated development of biodiversity and natural areas, coastal areas and natural resources,
- Actions to coordinate and strengthen prevention policies and risk management,
- Actions to promote the control of environmental impacts (pollution, waste management) and exploit the potential of renewable energy.

As part of this program, Egis has participate with the redaction of “**Guide for disaster risk prevention and reduction plan (PPR) in the Caribbean”**

The studies were conducted as part of a broad consultation to lead to a realistic document and reconciling the various interests at stake in particular between protection of property and lives and socio-economic development.

The Steering Committee has included consultants, services instructor of land occupation, the services responsible for alerts and evacuation of the population, the local and regional elective representative, ant the key economic players.

Methodologies of analysis and hazard mapping have been implemented in three steps:

- 1/ Classification of hazards, specifying how to perform data collection, field investigations and calculations. A high priority was given to qualitative studies requiring few resources;

- 2/ The evaluation of socio-economic or natural areas including housing vulnerable and strategic areas for emergency response, natural areas to preserved in order not to exacerbate the risks.

- 3/ The zoning regulations, and how to effectively communicate about the risks.

In this guide, the recommendation for risk mapping it a crossing between the flood levels map and issues map. The flood levels maps have to be done for the 1-in-100 years return period or the highest flood known.

As there is no design standard in Saint Lucia, we will apply this methodology approved in the whole Caribbean by the European Union.

2.2.3 World Bank design standards

Some drainage design standards are given by the World Bank in the “Guide to Integrated urban Flood Risk Management for the 21st Century” - 2012.

In this guide it is said that:

- **Flood hazard is usually estimated in terms of a rainfall event or ‘design flood’ such as the 100 year flood.**
- **Flood defenses are constructed to protect against flood events of a particular magnitude, expressed as risk in any one year: for example, defenses in urban areas may be built to provide protection against flood events of a size which might occur, on average, once in one hundred years.**
- **Climate change must be taken into account. But flood risk is dynamic and the large uncertainties associated with the estimates of future risk make its management under climate change a process of decision-making under deep uncertainty. It is necessary to take a robust approach.**

Chapter 3. Hydrological study

3.1 Catchment areas

3.1.1 Dennery

Figure 8 : Dennery 3D view from the bay *(Google Earth)*

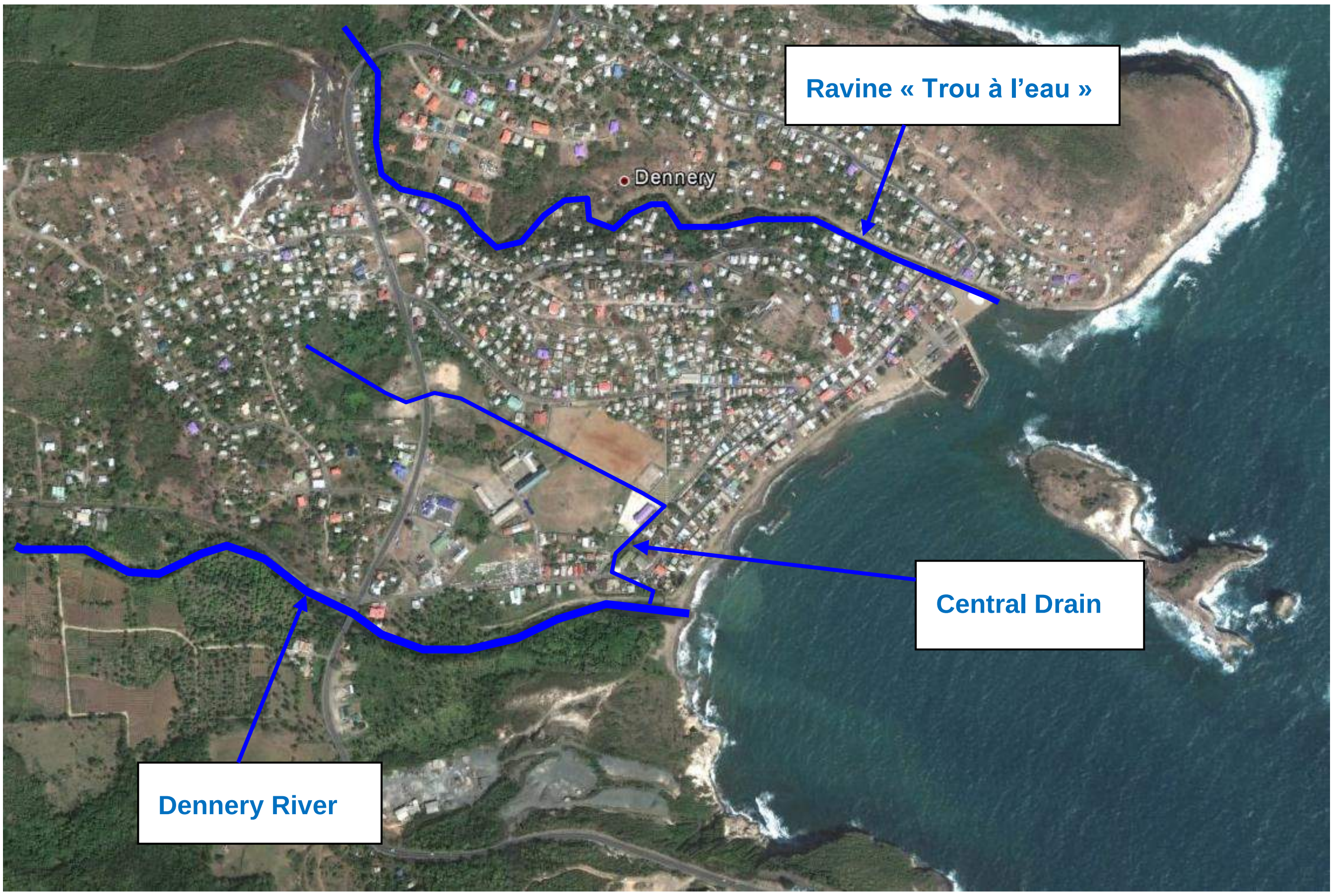


Figure 9 : Dennery aerial view *(Google Earth)*

<u>1/ Dennery River's watershed</u> characteristics are exposed below:

Total area :	18.3074 km²
Perimeter:	18.78 km²
Maximum altitude:	1 250 ft (~380 m)
Maximum length:	12 km
Average slope:	3.17%

Those data are evaluated by GIS software using the 1: 25 000 map of Saint Lucia.
Almost the entire area can be considered as natural.
The last kilometers (about 2,5km) before reaching the ocean, the river floodplain is cultivated with pineapples, mango trees, coconut trees (concerning the main productions).

2/ Getting north of Dennery River, can be found a small watershed called "**<u>Central Drain</u>**" on this study.

Its characteristics are:

Total area :	0.4167 km²
Perimeter:	3.01 km²
Maximum altitude:	350 ft (~107 m)
Maximum length:	1.1 km

- Average slope: 10 %

This area is very urbanized. The hill upstream, with steep slopes, has been recently urbanized. At the bottom of the hill the area is quite flat. There is a wetland, but which is getting smaller and smaller years after years: urbanization in the area is increasing the filling of this natural pond. The central drain becomes a concrete drainage channel and goes along the schools and sports fields, then reaches the densely urbanized zone of the center town. After multiple severe bends in town, the drain reaches the mouth of the Mole river.

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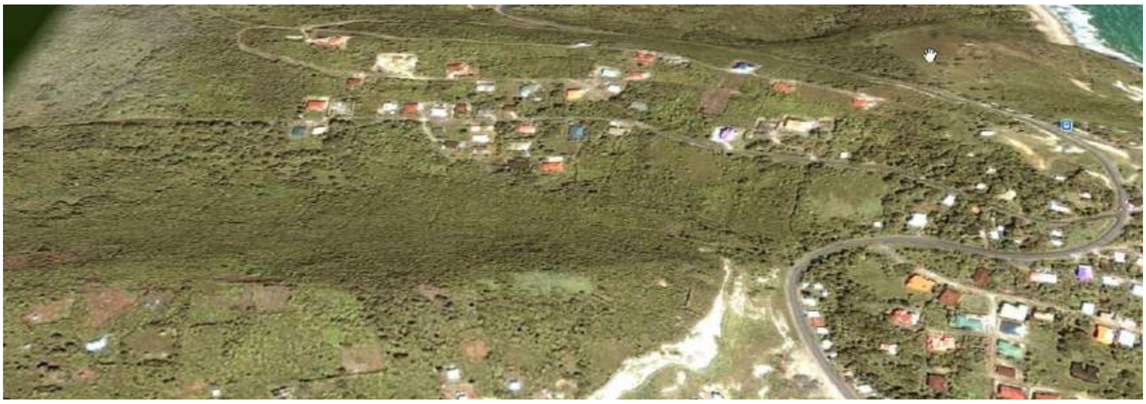
3/ Further in the north direction, the **Ravine Trou à l'Eau** watershed characteristics are:

Total area :	1.18087 km²
Perimeter:	5.53 km²
Maximum altitude:	617 ft (~190 m)
Maximum length:	2.8 km
Average Slope:	7 %

This watershed can be divided in two parts:

- Upstream from the main road: natural soils represent more than half part of the catchment although it is being more and more urbanized, as the next two photography can illustrate. This sub-catchment average slope is high;



Aerial photography from 2000 – upstream sub-catchment

Aerial photography from 2010 – upstream sub-catchment

- Downstream from the main road: the sub-catchment is more and more urbanized has it goes downstream. The ravine is natural and sinuous upstream and becomes a straight concrete channel in the last part. The drainage slope is slight and the bottom from the channel is influenced by the sea levels.

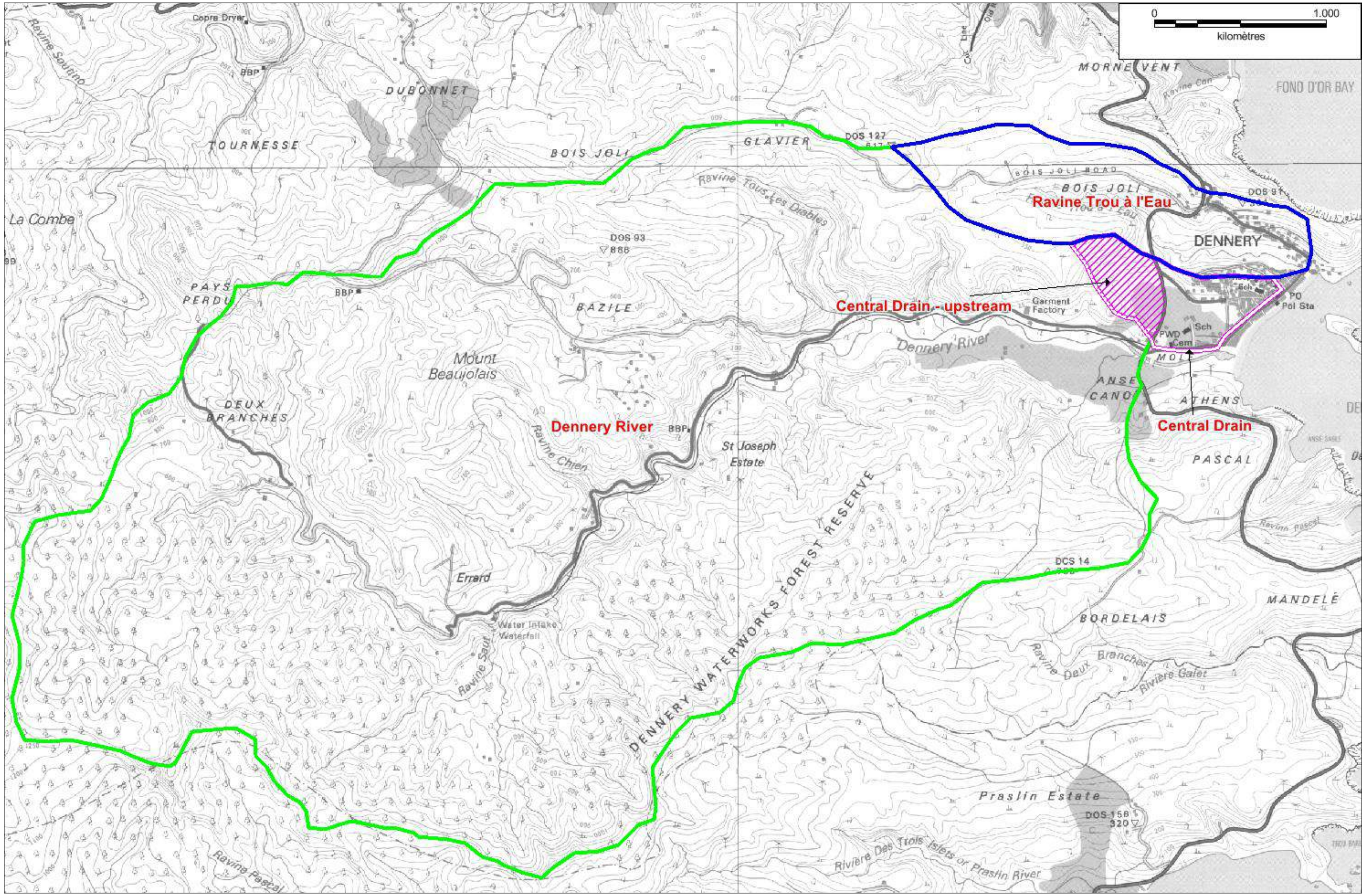


Figure 10 : Dennery watersheds

3.1.2 Soufrière & Fond Saint Jacques

Figure 11 : Soufriere town 3D view from the bay *(Google earth)*

Soufrière river (after the confluence with Sulphur Spring River):

- Total area : 13.2692 km^2
- Perimeter: 16.80 km^2
- Maximum altitude: 2 166 ft (~660 m)
- Maximum length: 8 km
- Average slope: 8.25%

Migny River (at Fond Saint Jacque upper bridge) :

- Total area : 1.3778 km^2
- Perimeter: 5.215 km^2
- Maximum altitude: 2100 ft (~190 m)
- Minimum altitude: 900 ft (~ 275 m)

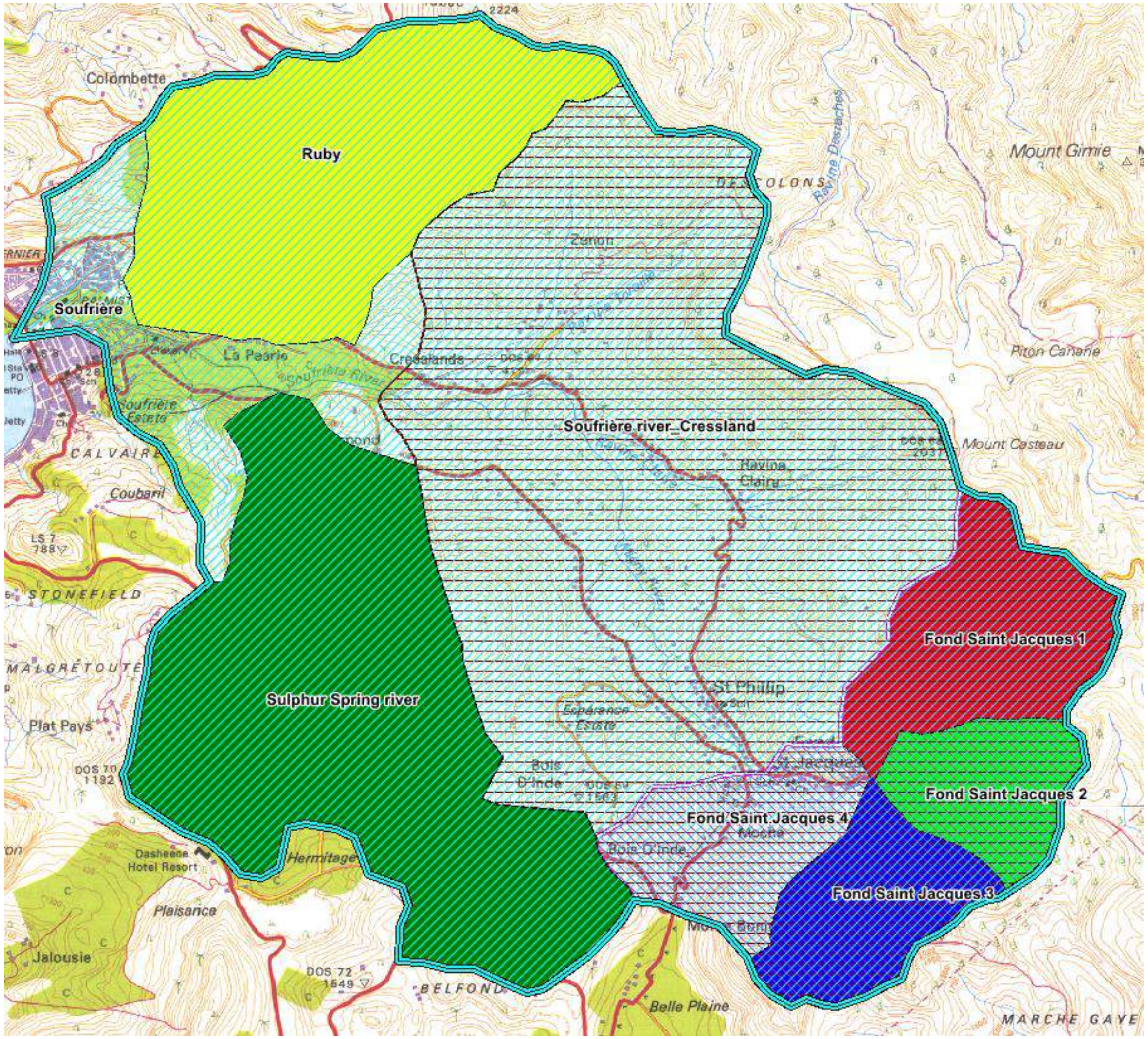


Figure 12 : Soufriere and Fond saint Jacques watersheds

3.2 Collected data

3.2.1 Hurricanes analysis

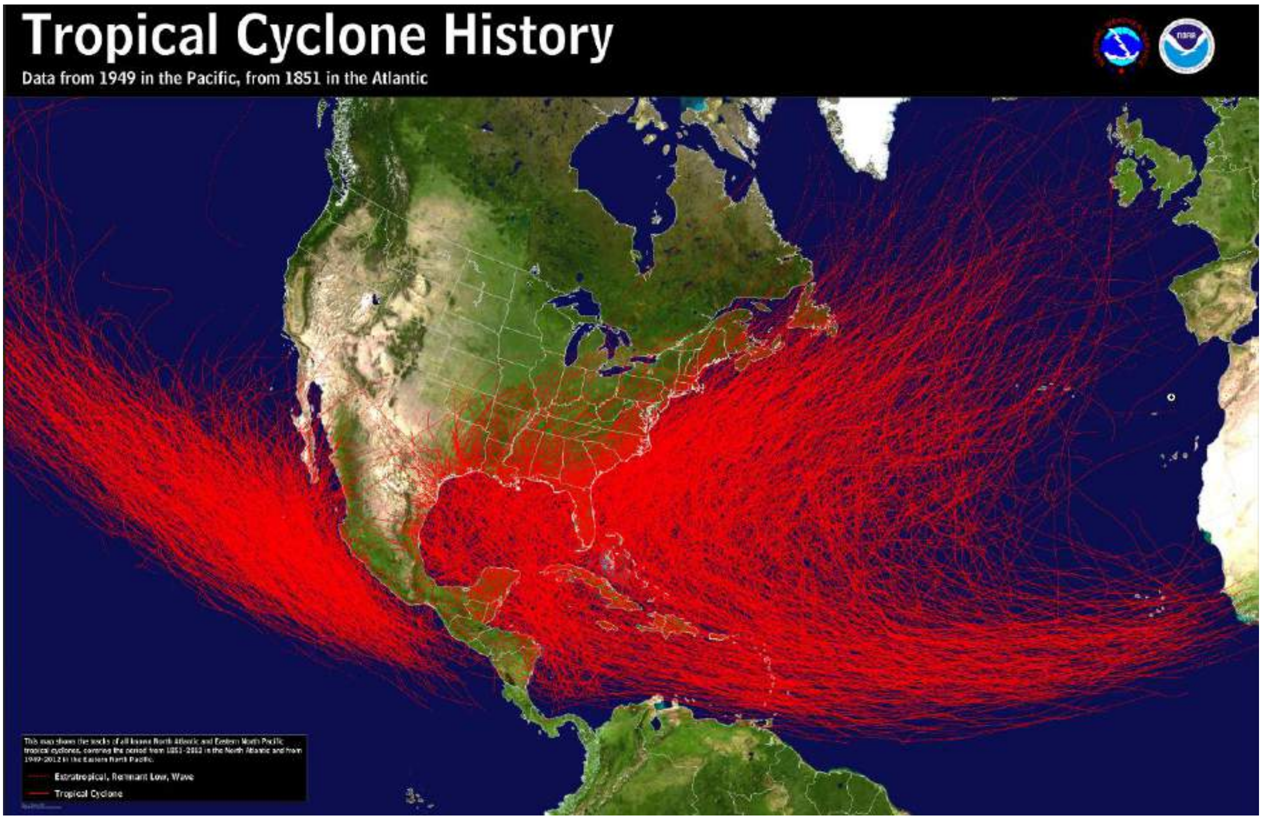
3.2.1.1 Hurricanes in Saint Lucia

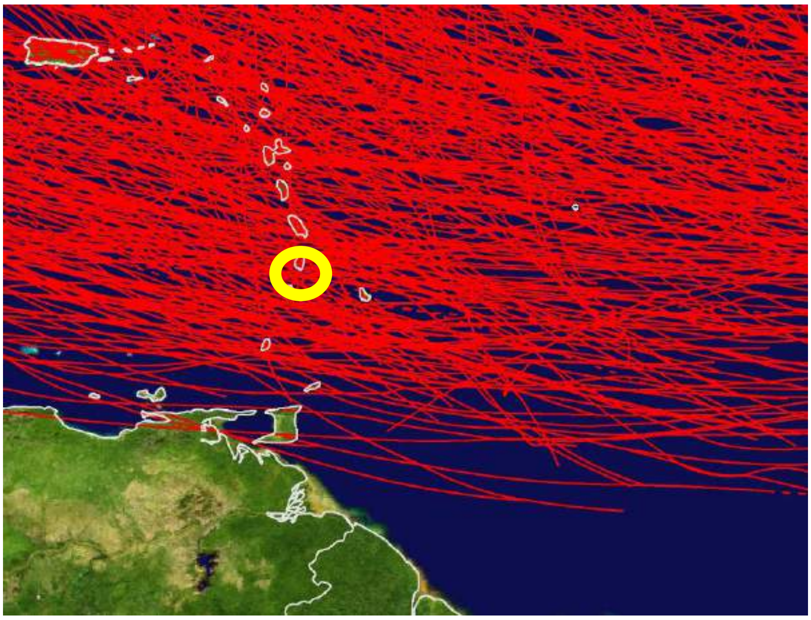
Hurricane Allen was devastating, causing extensive damage to Saint Lucia as a Category 3 storm. The storm claimed 9 lives and severely damaged infrastructure and agriculture. Tropical storm Debbie caused extensive damage in the agricultural sector and heavy rainfall resulted in extensive landslide in Saint Lucia. Most recently, Hurricane Dean in 2007 passed in the straits between Martinique and Saint Lucia. While a Category 2 storm, at that time, damage to Saint Lucia was estimated in excess of US$6 million due primarily to high winds, flooding and storm surge. While Hurricane Lenny (1999) did not directly impact Saint Lucia, waves generated by the storm had major coastal impacts. Damages from 6-meter waves were significant in Saint Lucia and throughout the island chain.

In 2010, Hurricane Tomas (category 2) damaged Saint Lucia. Throughout the hurricane's path, 71 people are known to have been killed, 14 of whom were in Saint Lucia. Monetary losses throughout the Windward Islands were estimated at US$588 million, mainly in Saint Lucia.

Source: National Hurricane Center (NHC)

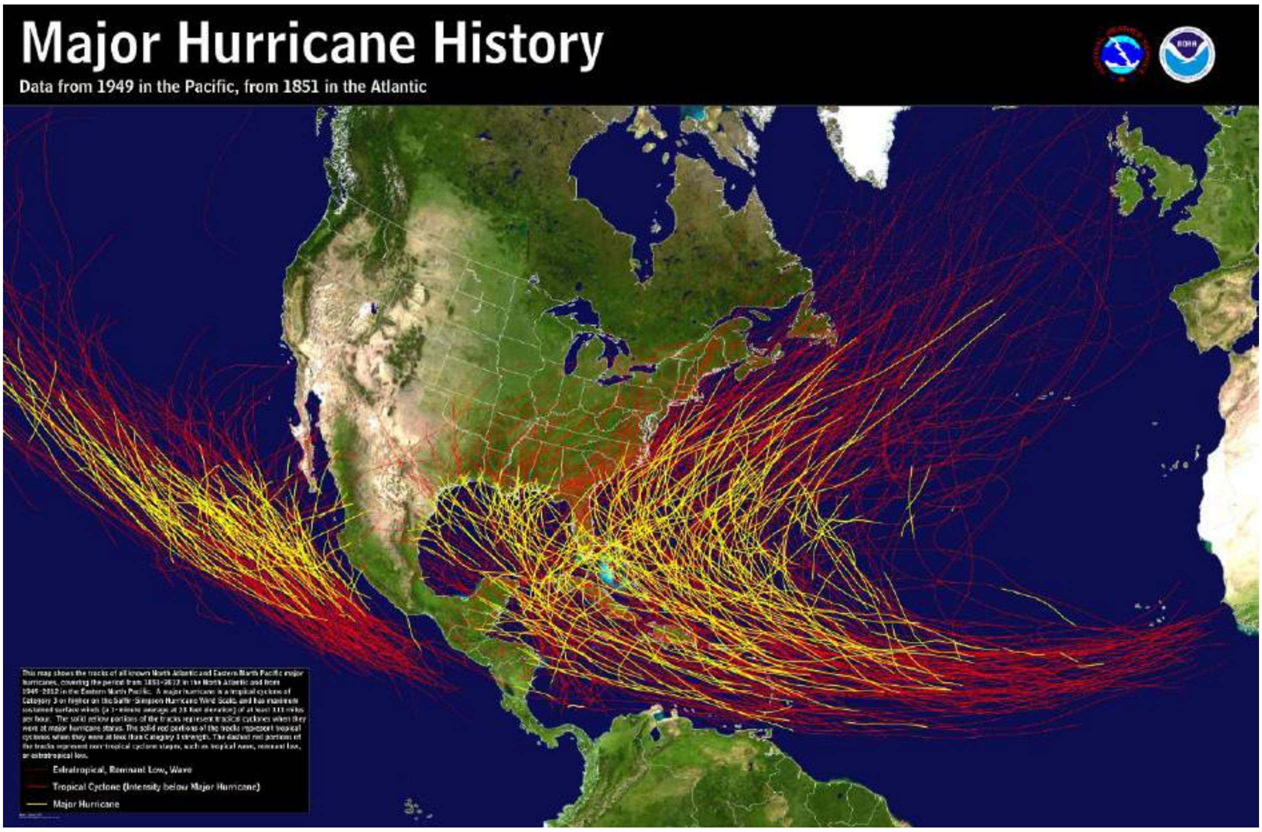
Figure 13 All the tropical cyclones since 1851 :





Zoom in the west indies

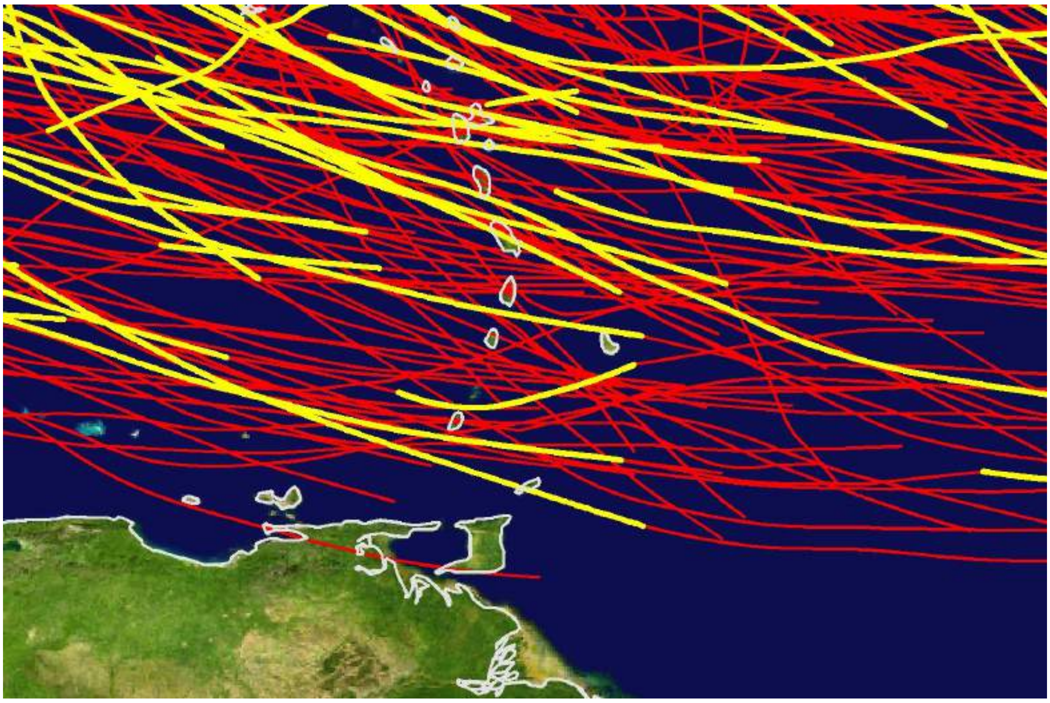
Figure 14 : All major hurricanes since 1851 (category 3 in yellow)



Major Hurricane History

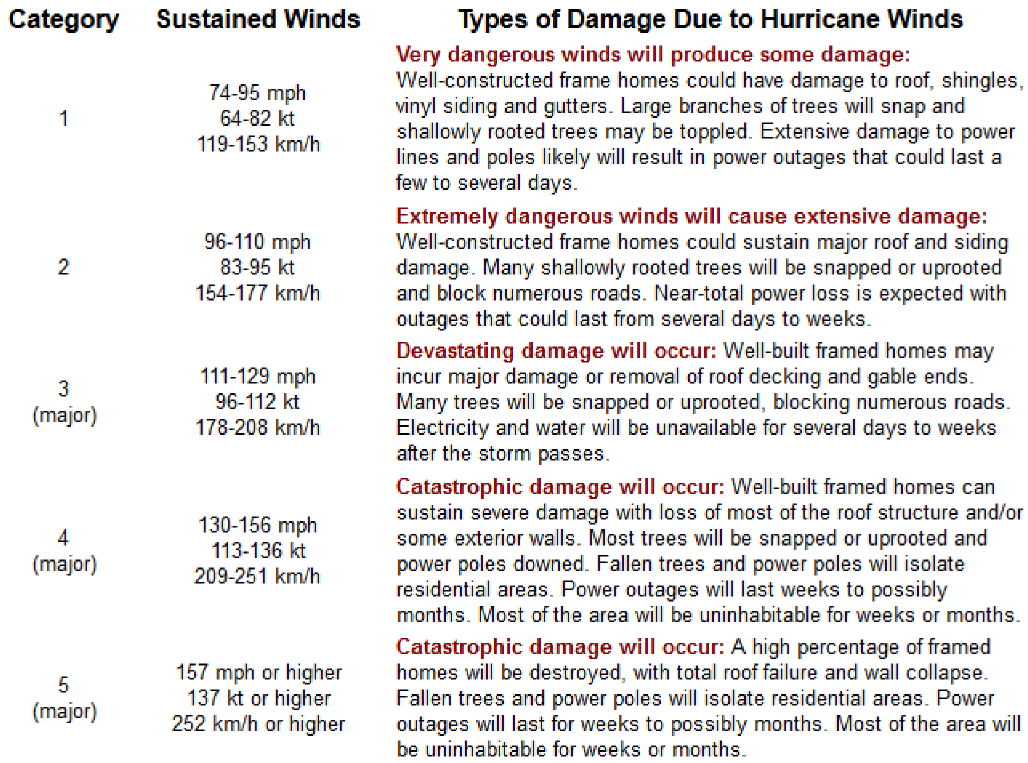
Data from 1949 in the Pacific, from 1851 in the Atlantic

This map shows the tracks of all known North Atlantic and Eastern North Pacific major hurricanes, covering the period from 1851-2012 in the North Atlantic and from 1949-2012 in the Eastern North Pacific. A major hurricane is a tropical cyclone of Category 3 or higher on the Saffir-Simpson Hurricane Wind Scale, and has maximum sustained surface winds (a 1-minute average at 33 feet elevation) of at least 111 miles per hour. The solid yellow portions of the tracks represent tropical cyclones when they were at major hurricane status. The solid red portions of the tracks represent tropical cyclones when they were at less than Category 3 strength. The dashed red portions of the tracks represent non-tropical cyclone stages, such as tropical wave, remnant low, or extratropical low.



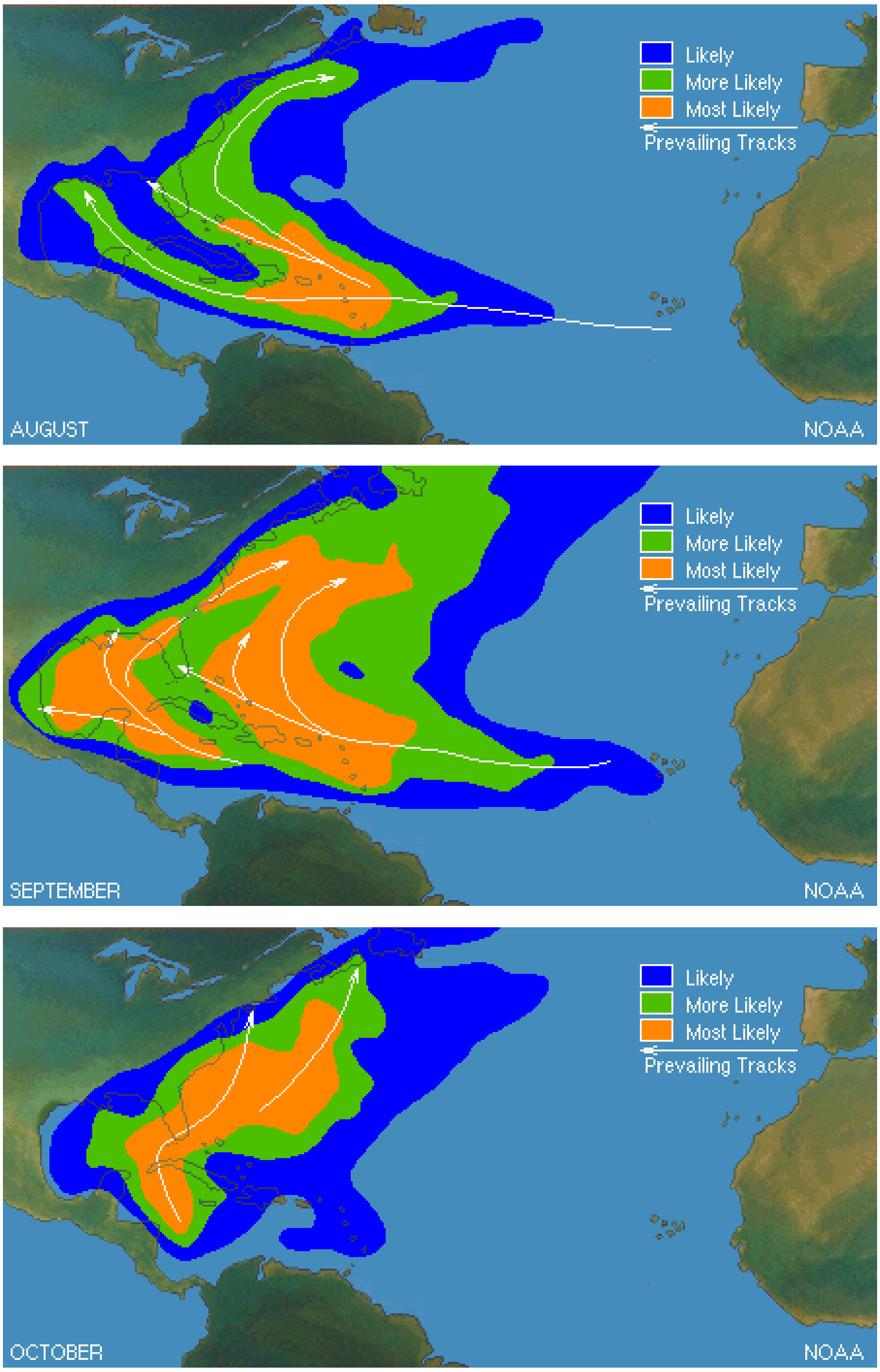
Zoom in the west indies

Saffir-Simpson scale (1 à 5) :



Category	Sustained Winds	Types of Damage Due to Hurricane Winds
1	74-95 mph 64-82 kt 119-153 km/h	**Very dangerous winds will produce some damage:** Well-constructed frame homes could have damage to roof, shingles, vinyl siding and gutters. Large branches of trees will snap and shallowly rooted trees may be toppled. Extensive damage to power lines and poles likely will result in power outages that could last a few to several days.
2	96-110 mph 83-95 kt 154-177 km/h	**Extremely dangerous winds will cause extensive damage:** Well-constructed frame homes could sustain major roof and siding damage. Many shallowly rooted trees will be snapped or uprooted and block numerous roads. Near-total power loss is expected with outages that could last from several days to weeks.
3 (major)	111-129 mph 96-112 kt 178-208 km/h	**Devastating damage will occur:** Well-built framed homes may incur major damage or removal of roof decking and gable ends. Many trees will be snapped or uprooted, blocking numerous roads. Electricity and water will be unavailable for several days to weeks after the storm passes.
4 (major)	130-156 mph 113-136 kt 209-251 km/h	**Catastrophic damage will occur:** Well-built framed homes can sustain severe damage with loss of most of the roof structure and/or some exterior walls. Most trees will be snapped or uprooted and power poles downed. Fallen trees and power poles will isolate residential areas. Power outages will last weeks to possibly months. Most of the area will be uninhabitable for weeks or months.
5 (major)	157 mph or higher 137 kt or higher 252 km/h or higher	**Catastrophic damage will occur:** A high percentage of framed homes will be destroyed, with total roof failure and wall collapse. Fallen trees and power poles will isolate residential areas. Power outages will last for weeks to possibly months. Most of the area will be uninhabitable for weeks or months.

Figure 15 : statistical tracks analysis on the 3 active months



3.2.1.2 Hurricane Tomas

Hurricane Tomas was the latest recorded tropical cyclone on a calendar year to strike the Windward Islands. The nineteenth named storm and twelfth hurricane of the 2010 Atlantic hurricane season, Tomas developed from a tropical wave east of the Windward Islands on October 29. Quickly intensifying into a hurricane, it moved through the Windward Islands and passed very near Saint Lucia. After reaching Category 2 status on the Saffir-Simpson scale, Tomas quickly weakened to a tropical storm in the central Caribbean Sea, due to strong wind shear and dry air. Tomas later regained hurricane status as it reorganized near the Windward passage.

The estimated maximum intensity of this hurricane, 85 kt, is based on a maximum 10- min wind observation of 77 kt from Hewanorra Airport in St. Lucia at 1926 UTC 30 October, adjusted by applying a gust factor of 1.11 to convert from a 10-min average to a maximum 1-min average (Harper et al. 2009). In addition, there was an SFMR-based surface wind measurement of 85 kt at 0537 UTC 31 October from the 53WRS.

Tomas produced phenomenal rainfall in St. Lucia, with totals ranging from 21 to 25 inches and a maximum total of 26.3 inches from Desraches over about a 23-h period.

Throughout the hurricane's path, 71 people are known to have been killed, 14 of whom were in Saint Lucia. Monetary losses throughout the Windward Islands were estimated at US$588 million, mainly in Saint Lucia.

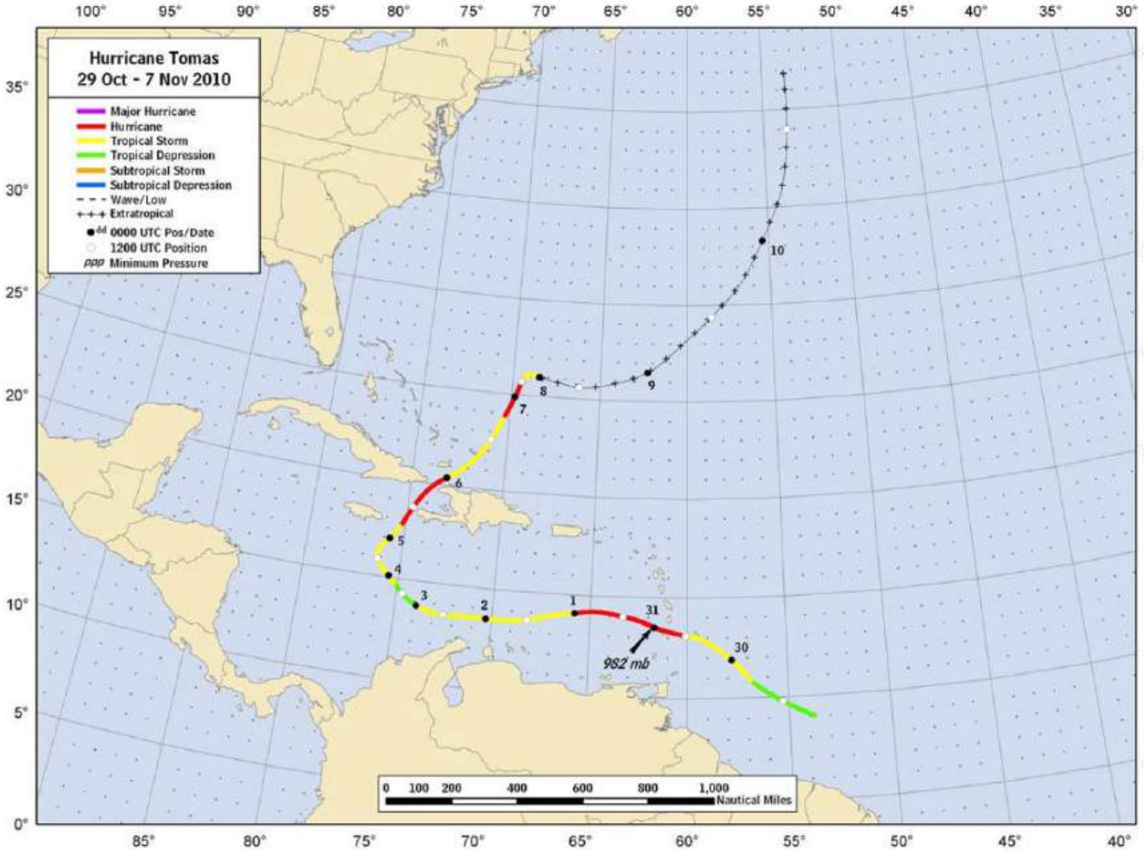


Figure 16 : best tracks position for hurricane Tomas

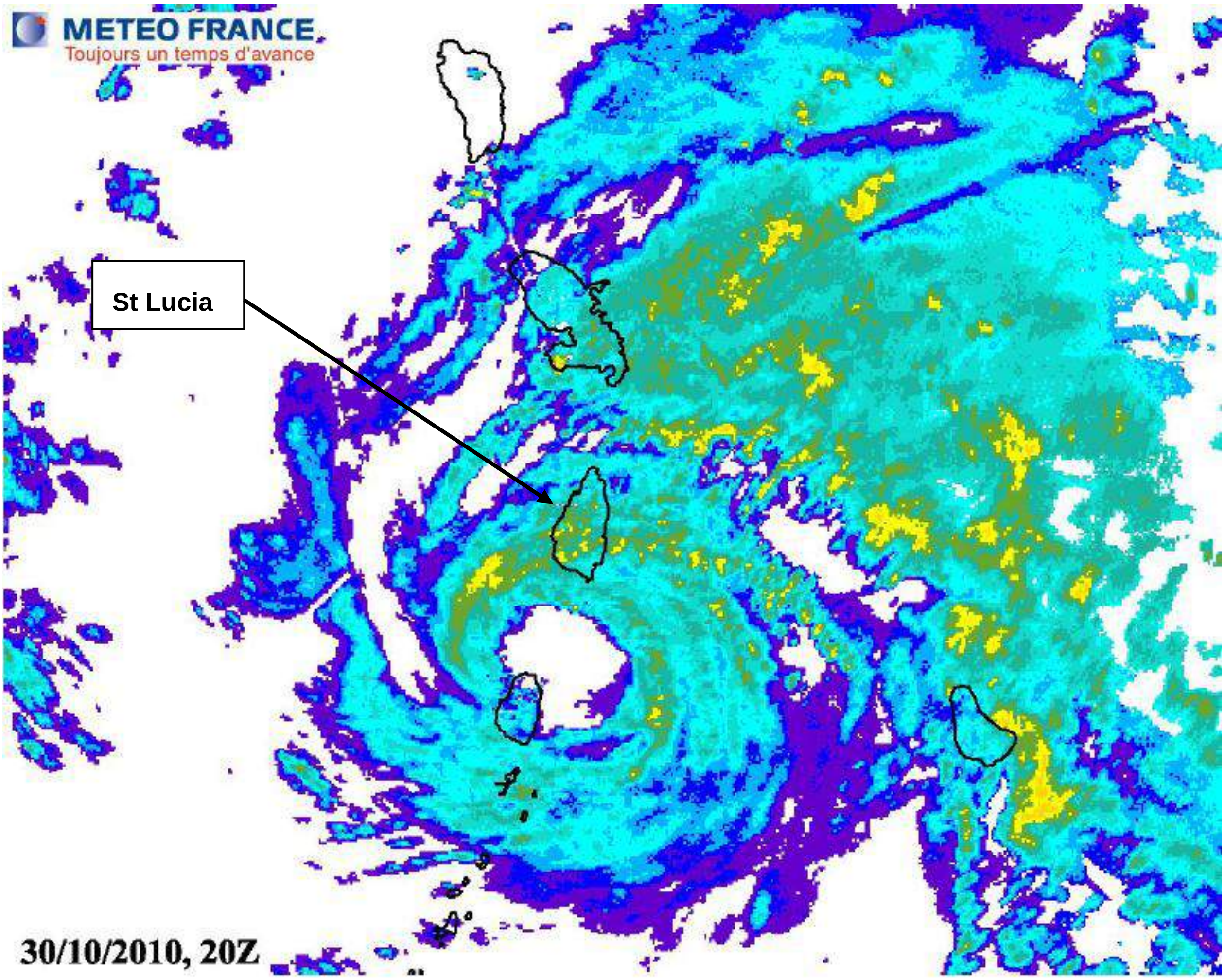


Figure 17 : Martinique radar image of hurricane Tomas at 2000 UTC

3.2.2 Rainfall Data

3.2.2.1 Rainfall stations in Saint Lucia

There are 34 rainfall stations in Saint Lucia for which rainfall data exist.

27 are still working today.

Most of them provide daily data except the two airports stations that provide hourly data.

The following stations can be useful in the studied area:

- Soufrière and Fond Saint Jacques:
    - Soufriere;
    - Edmund Forest;
    - Barthe Nursery;
    - Union Val Estate;
    - Desraches;
    - Delcer School;
    - Saltibus

- Dennery :
    - Mabouya;
    - CARDI;
    - Barre de l'Isle;
    - Millet;
    - Patience Estate;
    - Errard Estate;
    - Mamiku

Unfortunately, only few stations had collected data during Tomas: Union, CARDI and Patience + airports station.

Table 1 : available data in rainfall stations close to Dennery or Soufrière watersheds:

Station	Type	First year data	Last year data	Duration	Datas during Tomas
Patience	**Daily data**	**1955**	**2012**[1]	**58 years**	**Yes**
Mamiku Estate	Daily data	1955	2005	43	No
CARDI	**Daily data**	**1980**	**2012**	**31**	**Yes**

---

[1] When the last year is 2012 it means that the data has been collected until 2012 but that the station is still working today.

Station	Type	First year data	Last year data	Duration	Datas during Tomas
Millet	Daily data	1979	2012	22	no
Vigie Airport	**Daily data**	**1985**	**2012**	**27**	**Yes**
Barre de Lisle	Daily data	1955	1982	26	No
Barthe	Daily data	1955	2012	58	No
Delcer	Daily data	1985	2012	28	No
Edmund Forest	Daily data	1978	2009	32	No
Hewannora Airport	**Daily data**	**1982**	**2012**	**29**	**Yes**
Saltibus	Daily data	1985	2012	25	No
Soufrière	Daily data	1997	2012	14	No
Union	**Daily data**	**1955**	**2012**	**57**	**Yes**
Desraches	Daily data	1987	2009	23	No
Errard Estate	Daily data	1990	2012	23	No

For the first statistical analysis, we will focus on the stations working while Tomas.

Union and Patience seem to be the most interesting stations as they have the longest duration in collecting data.

The duration column in this table doesn’t mean that data do exist for every year: there are some lacks of data in every rainfall stations (malfunctioning or maintenance problems).

3.2.2.2 Rainfall distribution in Saint Lucia

The annual rainfall distribution in Saint Lucia is given in the figure 11, from “Vulnerability & adaptation assessment for water sector in Saint Lucia”, October 2010. The annual rainfall is between 1500mm in the coastal areas, and 4000mm in the mountainous part of the island. The upstream part of the studied watersheds, in the mountains, are in the most rain-fed part of the island. Soufriere watershed is more rain-fed annually than Dennery’s.

The studied rainfall stations are highlighted with red circles.

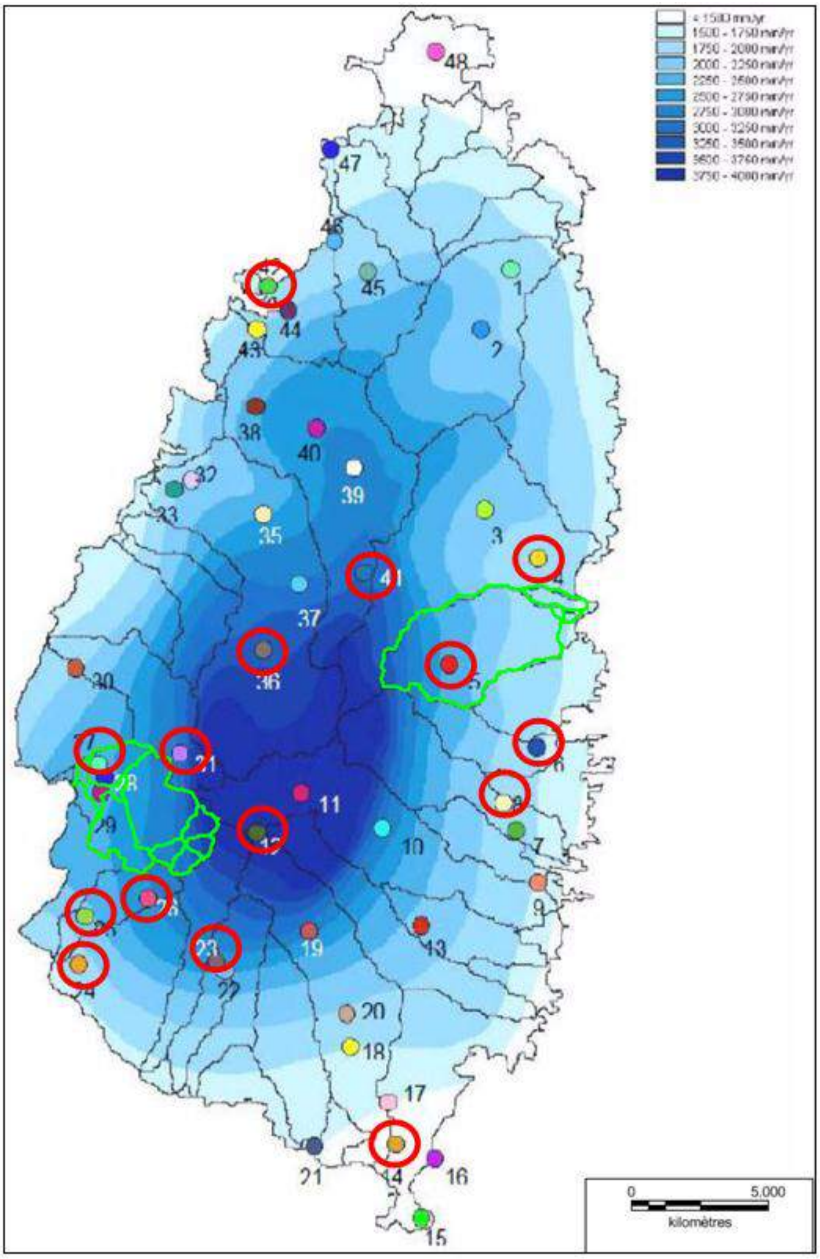


Figure 18 : Map of annual rainfall distribution, rainfall stations and studied watersheds

3.3 Peak flows calculations

3.3.1 Probability of occurrence of floods

Flood forecasts for a natural drainage area or a city are usually obtained by analyzing the past occurrence of flooding events, determining their recurrence intervals, and then using this information to extrapolate to future probabilities.

The probability of occurrence for pluvial, groundwater, flash, and semi-permanent floods is much more difficult to estimate, even if historical data is available. This is due to the fact that the causes of these types of floods are a combination of a meteorological event such as heavy rainfall and other factors such as insufficient drainage capacity, mismanagement of key infrastructure and other human factors.

For coastal floods caused by storms or hurricanes, their probability of occurrence can, in principle, be computed using historical data or numerical simulations of key variables such as wind speed, sea level, river flow and rainfall.

The return period:

The recurrence interval or return period is defined as the average time between events of a given magnitude assuming that different events are random. The recurrence interval or return period of floods of different heights varies from catchment to catchment, depending on various factors such as the climate of the region, the width of the floodplain and the size of the channel. In a dry climate the recurrence interval of a three meter height flood might be much longer than in a region that gets regular heavy rainfall. Therefore the recurrence interval is specific to a particular river catchment.

Since only the annual maximum discharge is considered, the amount of data available to perform the return period calculation can be very limited in some cases. In Europe and Asia, partial records extending over centuries may be found, as for instance in the case of sea floods in the Netherlands. In other places, like in Saint Lucia, data may be scarce and records are rarely longer than for 50 years. This poses an important limitation to the calculation of recurrence intervals which must be taken into account when evaluating and communicating uncertainties in flood probability estimations.

Once the recurrence intervals are determined based on the historical record, some assumption about the flood frequency distribution has to be made in order to extrapolate or interpolate to events that have not been recorded historically.

To achieve this, an assumption about the distribution of flood frequency has to be made. In this way the recurrence interval for any discharge (and not just those present in the observational record) can be inferred.

Flood probability:

The recurrence interval, as discussed above, refers to the past occurrence of floods, whilst flood probability refers to the future likelihood of events. The two concepts are related because the recurrence interval of past events is usually used to estimate the probability of occurrence of a future event:

For any discharge, or alternatively, any recurrence period, the probability of occurrence is the inverse of the return period $p=1/T$

Using the relationship between return period T and flood probability p, it is clear that a flood discharge that has a 100-year recurrence interval has a one percent chance of occurring (or being exceeded) in a given year. The term 'one hundred year flood' has often been used in relation to floods with a 100-year recurrence interval. This can be misunderstood, as a 100-year flood does not have a 100 percent chance of occurring within a 100 year period.

3.3.2 Statistical analysis in Saint Lucia

Statistical laws:

In probability theory and statistics, the **Gumbel distribution** is used to model the distribution of the maximum (or the minimum) of a number of samples of various distributions. Such a distribution might be used to represent the distribution of the maximum level of a river in a particular year if there was a list of maximum values for the past years. It is useful in predicting the chance that an extreme earthquake, heavy rain, flood or other natural disaster will occur.

Gumbel has shown that the maximum value (or last order statistic) in a sample of a random variable following an exponential distribution approaches the Gumbel distribution closer with increasing sample size.

In hydrology, therefore, the Gumbel distribution is used to analyze such variables as monthly and annual maximum values of daily rainfall and river discharge volumes, and also to describe droughts.

The cumulative distribution function of the Gumbel distribution is:

$$F(x;\mu,\beta) = e^{-e^{-(x-\mu)/\beta}}.$$

In probability theory, a **log-normal distribution** is a continuous probability distribution of a random variable whose logarithm is **normally distributed**. Thus, if the random variable X is log-normally distributed, then $Y = \log(X)$ has a **normal distribution**.

Likewise, if Y has a normal distribution, then $X = \exp(Y)$ has a log-normal distribution. A random variable which is log-normally distributed takes only positive real values.

Log-normal is also written log normal or lognormal. The distribution is occasionally referred to as the Galton distribution or Galton's distribution.

A variable might be modeled as log-normal if it can be thought of as the multiplicative product of many independent random variables each of which is positive. (This is justified by considering the central limit theorem in the log-domain.) For example rainfalls.

A normal distribution is :

$$f(x,\mu,\sigma)=\frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

Patience

From the daily data between 1955 and 2012, we have extracted the annual maximum daily rain.

As we can see on the following table, three years do not have any data.

For Patience rainfall station **56 years** can be used for the statistical analysis.

year	Maximum daily value per year
1955	177.8
1956	100.1
1957	69.9
1958	76.2
1959	104.1
1960	63.5
1961	59.7
1962	108.5
1963	116.8
1964	86.9
1965	126.2
1966	109.2
1967	156.5
1968	112.5
1969	119.6
1970	183.4
1971	0
1972	132.6
1973	56.9
1974	128.3
1975	137.2
1976	91.4
1977	119.4
1978	71.1
1979	119.4
1980	111.8
1981	68.6
1982	99.1
1983	82.3
1984	102.1
1985	56.6
1986	104.6
1987	90.4
1988	101.1
1989	101.1
1990	81.5
1991	78.5
1992	98.8
1993	65.6
1994	50.1
1995	142.1
1996	122.1
1997	116
1998	87.8
1999	68
2000	103.4
2001	40.6
2002	0
2003	62.2
2004	44.6
2005	63
2006	51.2
2007	141.6
2008	97
2009	60.2
2010	480.4
2011	102
2012	122

Table 2 : Maximum daily rainfall per year in Patience rainfall station

The first thing we can see is the big difference between the maximum value and the second one: 480 mm measured in 2010 (with Tomas) and 183.4 mm the year 1970.

We tried to found a correlation between the return period and the daily rainfall by different statistical adjustments (Gumbel or log-normal).

Figures in the next page show that the adjustments cannot be considered for a long time return period. **After about 1 in 20 years return period, there is not enough value to permit an efficient adjustment.**

There is not enough data to characterize Tomas rainfall which was very high comparing to the other data collected by the station.

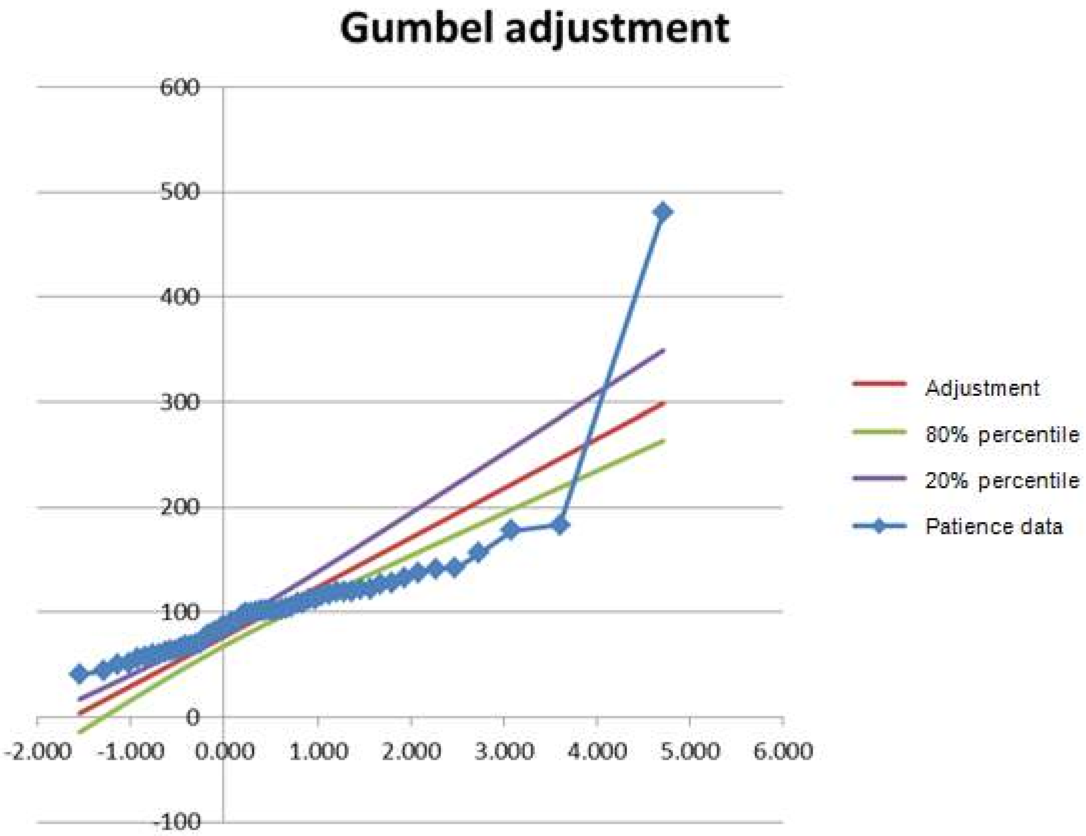


Figure 19 : Gumbel adjustment for Patience rainfall station

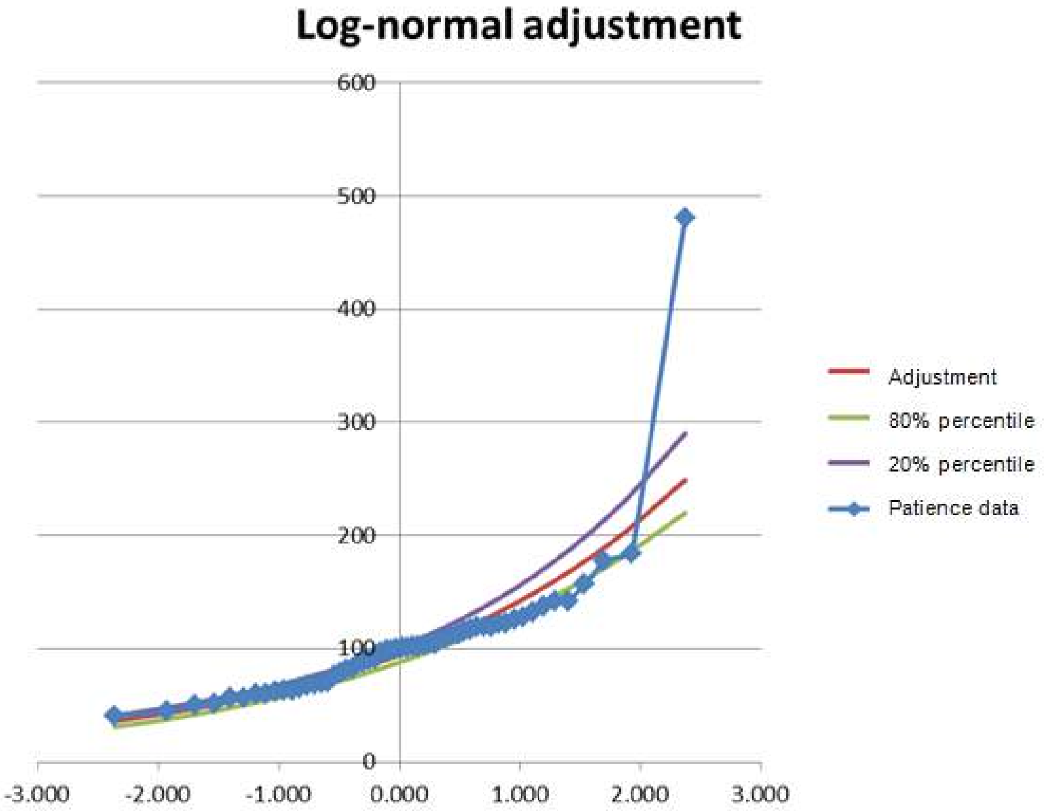


Figure 20 : Log-normal adjustment for Patience rainfall station

Cardi

From the daily data between 1955 and 2012, we have extracted the annual maximum daily rain.

As we can see on the following table, a lot of years do not have any data.

For Cardi rainfall station **32 years** can be used for the statistical analysis.

year	Maximum daily value per year
1980	127.6
1981	142.5
1982	104.7
1983	84.4
1984	146.7
1985	45
1986	114.3
1987	185.4
1988	97
1989	88.5
1990	27.2
1992	90.3
1993	93
1994	72.4
1995	81.1
1996	80.5
1997	77.6
1998	104
1999	69.3
2000	114.5
2001	91.6
2002	74.5
2003	68.4
2004	108.8
2005	119.5
2006	120
2007	119.2
2008	88.1
2009	67.8
2010	541.2
2011	89.6
2012	77.3

Table 3 : Maximum daily rainfall per year in Cardi rainfall station

The same comment can be done for the difference between maximum rainfall data and the second maximum: 541.2 mm in 2010 during Tomas and 185.4 mm in 1987.

We tried to found a correlation between the return period and the daily rainfall by different statistical adjustments (Gumbel and Log-normal).

Figures in the next page show that the adjustments cannot be considered for a long time return period. **After about 1 in 10 years return period, there is not enough value to permit an efficient adjustment.**

There is not enough data to characterize Tomas rainfall which was very high comparing to the other data collected by the station.

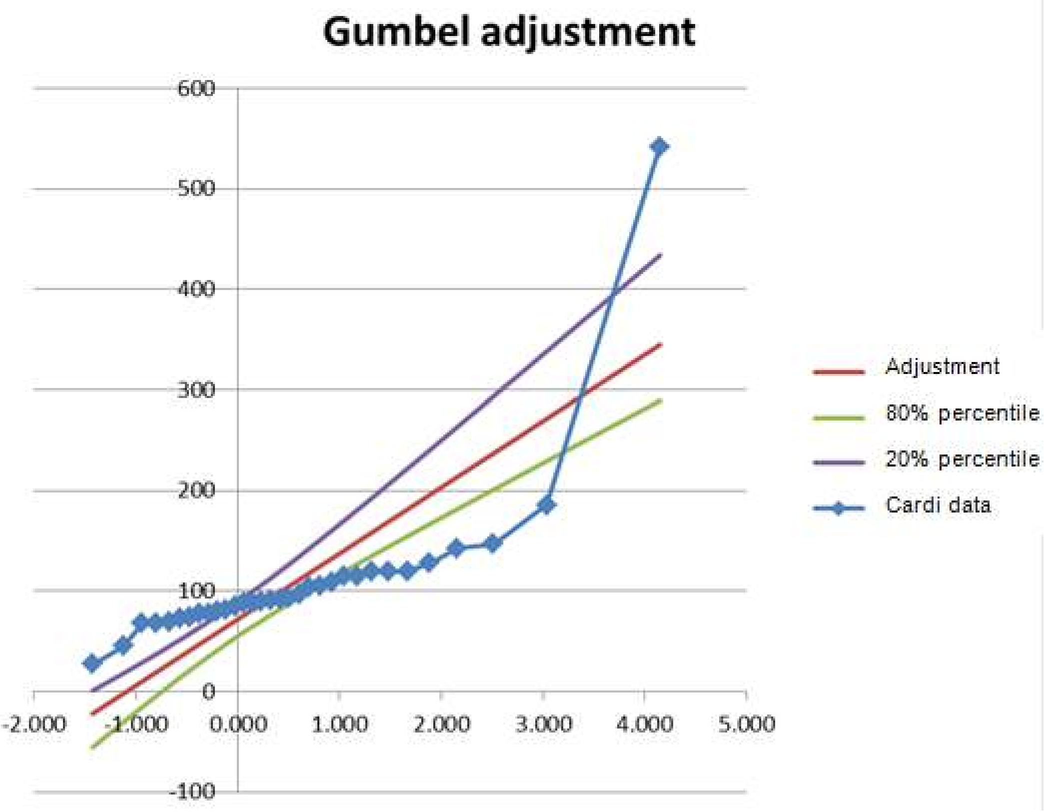


Figure 21 : Gumbel adjustment for Cardi rainfall station

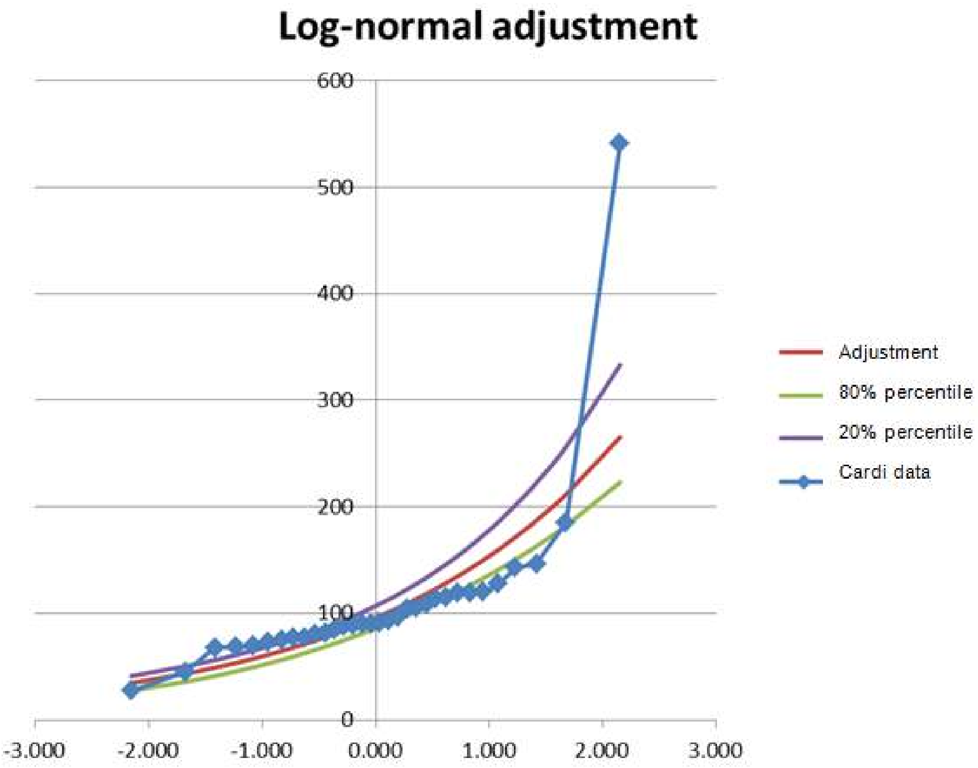


Figure 22 : Log-normal adjustment for Cardi rainfall station

Vigie Airport

From the daily data between 1955 and 2012, we have extracted the annual maximum daily rain.

As we can see on the following table, a lot of years do not have any data.

For Vigie Airport rainfall station **28 years** can be used for the statistical analysis.

year	Maximum daily value per year
1985	63.1
1986	108.4
1987	105.3
1988	270.1
1989	117.8
1990	150.2
1991	51.1
1992	105
1993	77.1
1994	238
1995	85.5
1996	204.4
1997	89.3
1998	75.2
1999	93
2000	78.2
2001	75.7
2002	90.2
2003	62.9
2004	100.2
2005	91.8
2006	104.8
2007	92.1
2008	95.5
2009	60.7
2010	533.3
2011	110.6
2012	71.8

Table 4 : Maximum daily rainfall per year in Vigie Airport rainfall station

The same comment can be done for the difference between maximum rainfall data and the second maximum: 533.3 mm in 2010 (Tomas) and 270.1 mm in 1988 (Gilbert Tropical Strom).

We tried to found a correlation between the return period and the daily rainfall by different statistical adjustments (Gumbel and Log-normal).

Figures next page show that the adjustments cannot be considered for a long time return period. **After about 1 in 10 years return period, there is not enough value to permit an efficient adjustment.**

There is not enough data to characterize Tomas rainfall which was very high comparing to the other data collected by the station.

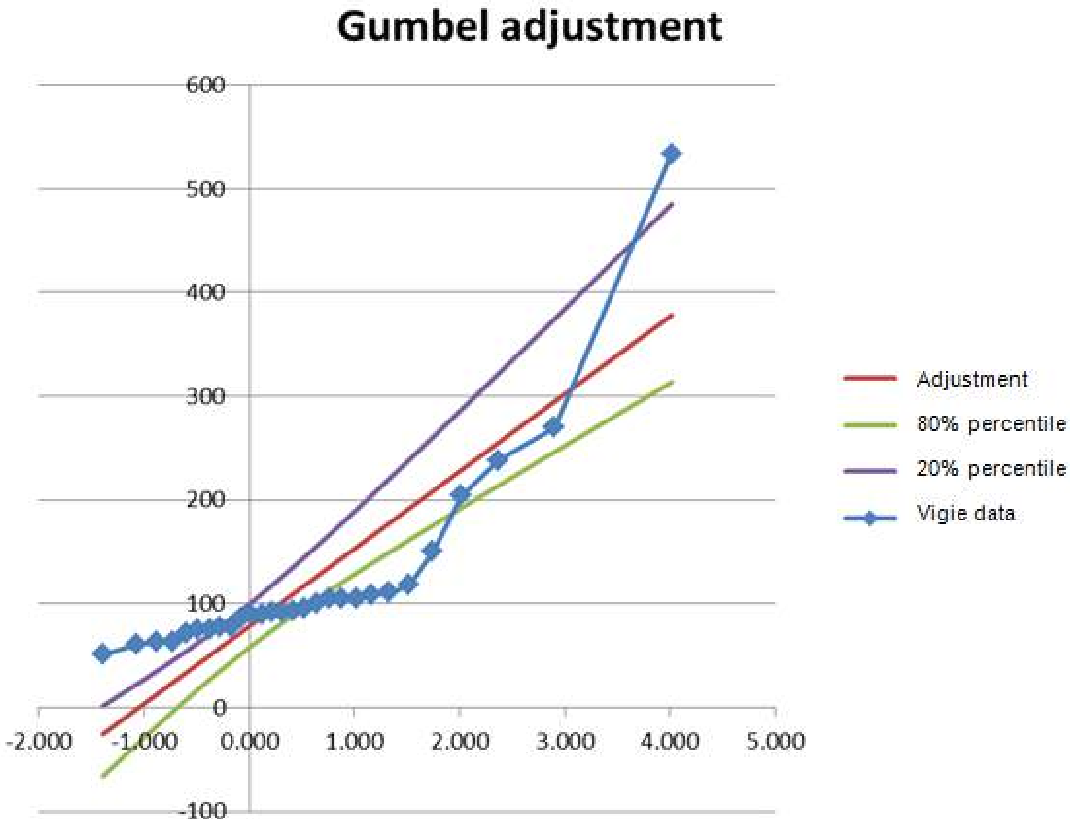


Figure 23 : Gumbel adjustment for Vigie Airport rainfall station

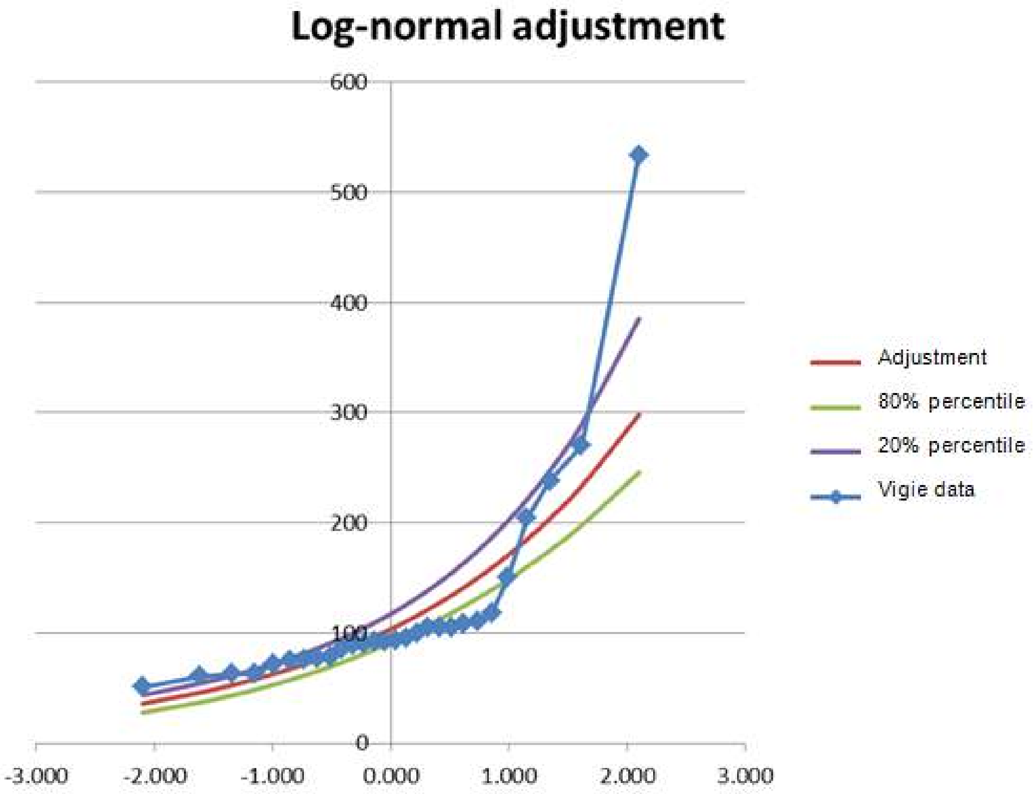


Figure 24 : Log-normal adjustment for Vigie Airport rainfall station

Hewannora Airport

From the daily data between 1982 and 2012, we have extracted the annual maximum daily rain.

As we can see on the following table, two years do not have any data (1983 - 1984).

For Hewannora Airport rainfall station **29 years** can be used for the statistical analysis.

year	Maximum daily value per year
1982	57.4
1985	138.8
1986	95
1987	58.7
1988	193.4
1989	245.3
1990	62.7
1991	58.5
1992	97.2
1993	89.7
1994	212
1995	122.6
1996	205.9
1997	58.7
1998	105.2
1999	115.6
2000	133.4
2001	80
2002	98.4
2003	49.9
2004	72.1
2005	128
2006	70.6
2007	53.3
2008	66.8
2009	65
2010	593.1
2011	134.5
2012	78.4

Table 5 : Maximum daily rainfall per year in Hewannora Airport rainfall station

The same comment can be done for the difference between maximum rainfall data and the second maximum: 593.1 mm (Tomas) and 245.3 mm in 1989 (Hugo Hurricane).

We tried to found a correlation between the return period and the daily rainfall by different statistical adjustments (Gumbel and Log-normal).

Figures next page show that the adjustments cannot be considered for a long time return period. **After about 1 in 10 years return period, there is not enough value to permit an efficient adjustment.**

There is not enough data to characterize Tomas rainfall which was very high comparing to the other data collected by the station.

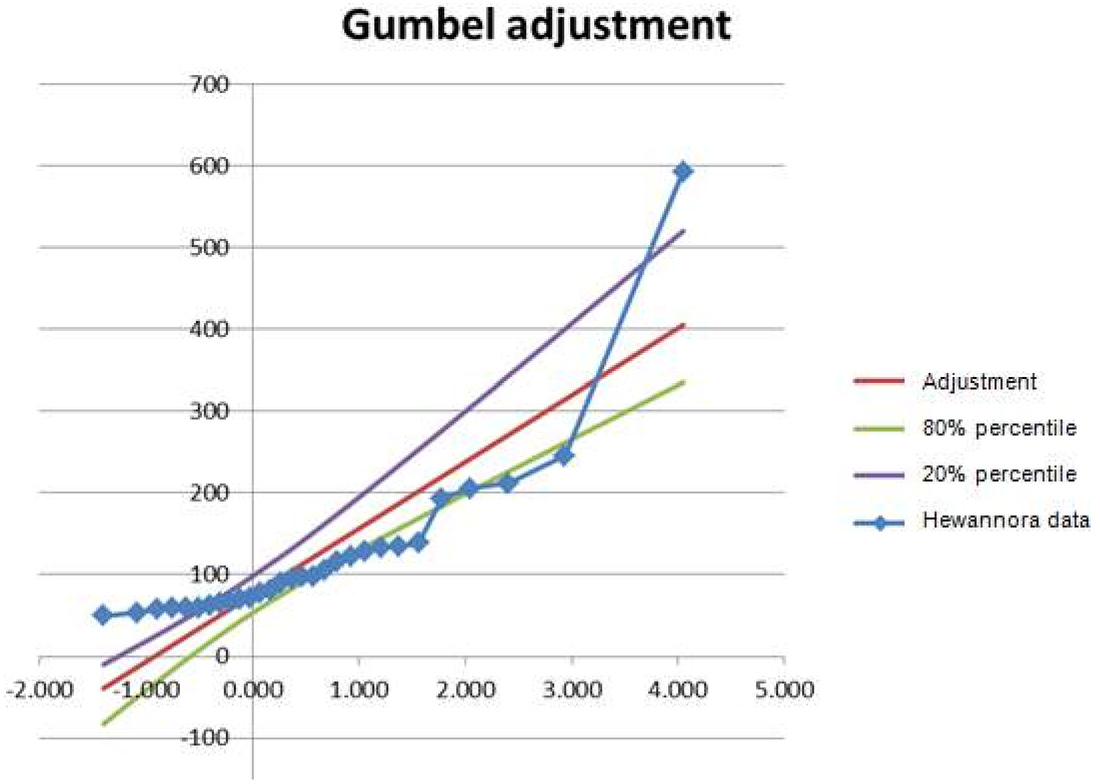


Figure 25 : Gumbel adjustment for Hewannora Airport rainfall station

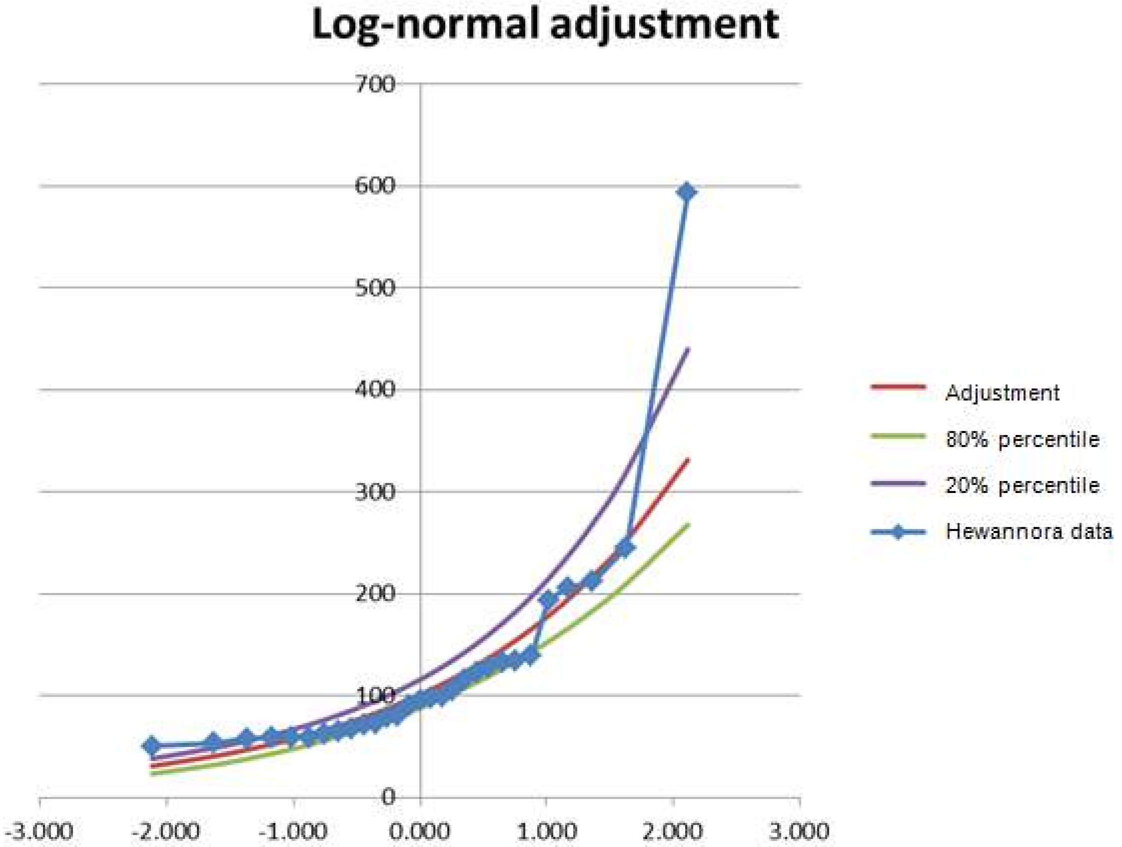


Figure 26 : Log-normal adjustment for Hewannora Airport rainfall station

Union

From the daily data between 1955 and 2012, we have extracted the annual maximum daily rain.

For Union rainfall station **58 years** can be used for the statistical analysis.

year	Maximum daily value per year
1955	99.1
1956	74.9
1957	66
1958	66
1959	53.3
1960	155.2
1961	66.3
1962	152.1
1963	114.6
1964	89.4
1965	113
1966	118.1
1967	293.4
1968	149.4
1969	129.3
1970	232.2
1971	139.7
1972	85.9
1973	69.1
1974	114.3
1975	82
1976	139.4
1977	124.7
1978	102.9
1979	95
1980	88.1
1981	160.5
1982	111.8
1983	63.5
1984	105
1985	86.7
1986	94
1987	136.4
1988	225.3
1989	107.9
1990	72.5
1991	85.1
1992	139.2
1993	77
1994	275.6
1995	95
1996	125
1997	75.8
1998	99
1999	69.4
2000	98.8
2001	72.6
2002	118.4
2003	59.8
2004	125
2005	171.6
2006	93.5
2007	100.8
2008	176
2009	91.1
2010	549
2011	127.6
2012	118.3

Table 6 : Maximum daily rainfall per year in Union rainfall station

The same comment can be done for the difference between maximum rainfall data and the second maximum: 549 mm (Toma)s and 293.4 mm in 1967 (Beulah tropical storm).

We tried to found a correlation between the return period and the daily rainfall by different statistical adjustments (Gumbel and Log-normal).

Figures next page show that the adjustments cannot be considered for a long time return period. **After about 1 in 10 years return period, there is not enough value to permit an efficient adjustment.**

There is not enough data to characterize Tomas rainfall which was very high comparing to the other data collected by the station.

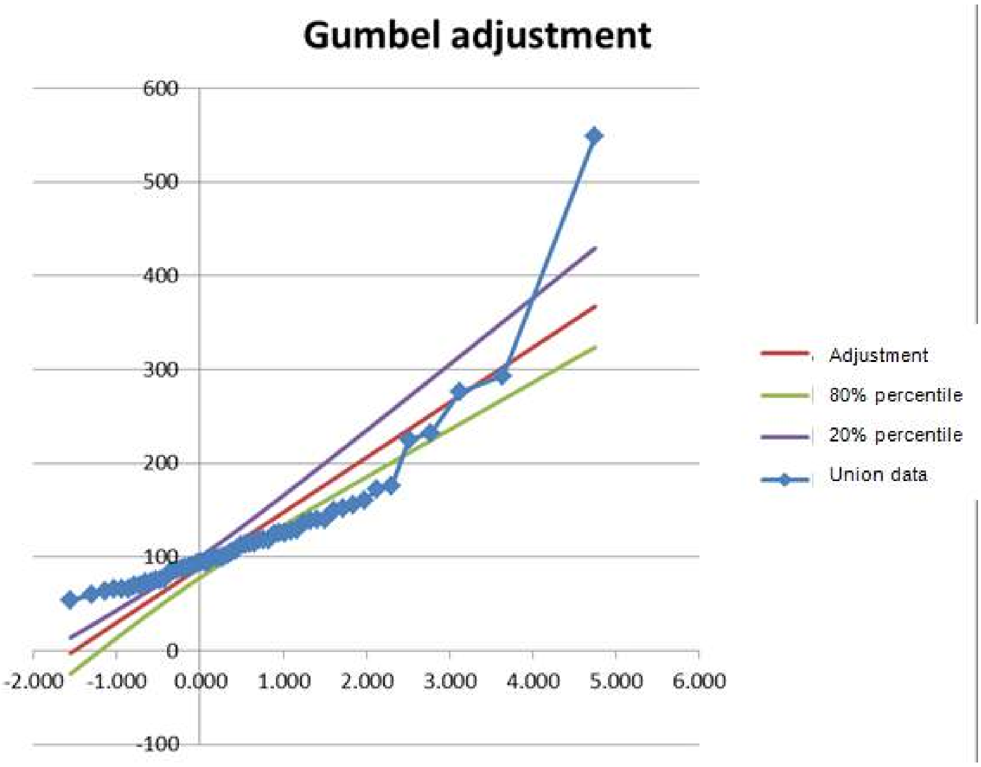


Figure 27 : Gumbel adjustment for Union rainfall station

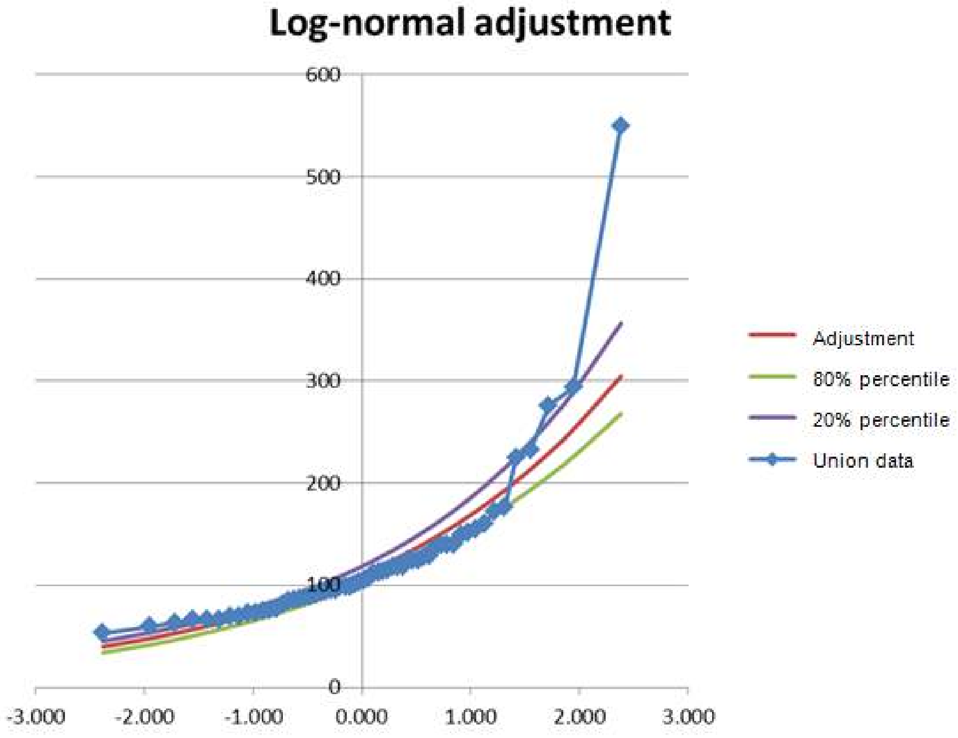


Figure 28 : Log-normal adjustment for Union rainfall station

3.3.3 Martinique statistical rainfall analysis

As we can see with the statistical analysis on Saint Lucia’s rainfall stations, the allowable data are not efficient to estimate the rare return period of rainfall.

Moreover, there is no analysis existing that tried to correlate rainfall and flows in the rivers. Just a few flow gauges exist in the island of saint Lucia but they have been installed a few years ago and don’t have enough data to statistical analysis..

Consequently, we decide to use the statistical analysis that exists in Martinique Island for different reasons:

- Both islands are separated by only 33 km and have a similar climate;
- In Martinique, rainfall data have been studied since 1920, and flow gauges since 1950;
- Watersheds can be very similar with a lot of rainfall in mountainous sub-catchments (high altitude), with steep slopes;
- Two famous organisms (ORSTOM and CEMAGREF[2]) have completed analysis on data and found a correlation between annual rainfall, return period and the length of the rainfall.

Details on this analysis are given in the technical book « *Les torrents du nord-ouest de la Martinique ; hydrologie des crues, erosion, hydraulique et dynamique torrentielles* » by Meunier, M.

A summary is given at the end of the report.

The correlation is given here:

P(T, d) = xo + Gradex * (-ln(-ln(1-1/T))

Where:

P correspond to the rainfall in mm for the return period T et the length of rainfall d;

Xo and the Gradex are two parameters depending on the annual rainfall and on the length of the studied rainfall.

This methodology is used all over the Martinique to determine design rainfall and then design flow in major infrastructures projects.

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[2] ORSTOM is the Scientist Research Office of French overseas territories. CEMAGREF is the National Center of Forest, water, Agricultural and Rural Engineering.

3.3.4 Peak flows evaluation and hydrographs in Dennery

The first data needed to use Martinique's equation are the annual rainfall data. This parameter has been determined for each watershed using the different classes of rainfall distribution (Cf. Figure 11) and its surface.

After knowing the local Saint Lucia's rainfall for different return period, we determine the maximum flow with the rational method as it is recommended in Martinique's watersheds calculations.

The rational formula is:

$$Q = C\,i\,A$$

Where:

Q = Peak rate of runoff in cubic meter per second

C = Runoff coefficient, an empirical coefficient representing a relationship between rainfall and runoff

i = Average intensity of rainfall for the time of concentration (T_c) for a selected design storm

A = Drainage area in square meters

For this method, it is assumed that a rainfall duration equal to the time of concentration results in the greatest peak discharge. The time of concentration is the time required for runoff to travel from the most distant point of the watershed to the outlet. Intuitively, once a rainfall event begins the amount of water flowing out of the watershed will begin to increase until the entire watershed is contributing water, at the time of concentration.

In order to determine the time of concentration, you first must determine the hydraulic length, or flow path. The hydraulic length is the distance between the most distant point in the watershed and the watershed outlet.

The runoff coefficient is used to fit the Rational Method to the particular drainage area being considered. In general, areas with permeable soils, flat slopes, and dense vegetation should have the lowest values, meaning that only a small percentage of rainfall will turn into runoff in these areas. Areas with dense soils, moderate to steep slopes, and sparse vegetation should be assigned the highest values which means that most of the water falling as rain will turn into runoff in these areas.

The following runoff coefficient has been used. They are classically used for tropical countries (used in Martinique for example for the same type of watersheds).

- 1-in-10 coefficient: 0.6;
- 1-in-50 coefficient: 0.75;
- 1-in-100 coefficient: 0.8;

Results are mentionned in this table :

Catchment	Area (km²)	Concentration time (mn)	1-in-10 flow (m^3/s)	1-in-50 flow (m^3/s)	1-in-100 flow (m^3/s)
Dennery River	18.31	143	**126**	**209**	**246**
Ravine Trou à l'Eau	1.18	30	**17**	**28**	**33**
Central Drain	0.42	13	**9**	**14**	**17**
Upstream Sub-catchment of Central Drain	0.18	6	**5**	**8**	**9**

Table 7 : Peak flows calculations in Dennery

Those calculations show that about 80% of total peak flows that can arrive in Dennery town are due to the Dennery River.

The concentration time of the main river is more than 2 hours, while the others catchments areas are responding in less than 30 minutes.

3.3.5 Peak discharge evaluation in Soufriere

The same Martinique's method, adapted to Saint Lucia's rainfalls, is used in Soufriere to determine peak flows.

Results are mentionned in this table:

Catchment	Area (km²)	Concentration time (mn)	1-in-10 flow (m^3/s)	1-in-50 flow (m^3/s)	1-in-100 flow (m^3/s)
Soufrière River at Cressland	9.24	55	**113**	**184**	**215**
Sulphur Spring River	3.44	36	**50**	**81**	**94**
Ruby	2.27	19	**44**	**70**	**82**
Soufrière River (entire Catchment)	16.19	65	**179**	**321**	**343**

Table 8 : Peak flows calculations in Soufriere

The concentration time is very short: it is about 1 hour, and the peak flows very high (comparing to Dennery river catchment), due to a more heavy rain catchment area and steep slopes.

3.3.6 Peak discharge evaluation in Fond Saint Jacques

3.3.6.1 The particularity of Fond saint Jacques : landslides floods

Fond Saint Jacques is situated in the mountains, along a ravine and surrounded by steep slopes. The landslide risk associated with flash floods risk cause devastating mudflows and debris flows in the area. Those debris flows can't be estimated, as it is not possible to determine the amount of cubic meters of debris that could collapse during a rainfall event.

Only water flows can be evaluated in the following paragraph.

3.3.6.2 1-in-10, 1-in-50 and 1-in-100 river peak flows and hydrographs

The same Martinique's method, adapted to Saint Lucia's rainfalls, is used in Fond Saint Jacques to determine peak flows.

Results are mentionned in this table:

Catchment	Area (km²)	Concentration time (mn)	1-in-10 flow (m^3/s)	1-in-50 flow (m^3/s)	1-in-100 flow (m^3/s)
Fond Saint Jacques 1	0.99	15	**23**	**36**	**42**
Fond Saint Jacques 2	0.55	6	**18**	**28**	**32**
Fond Saint Jacques 3	0.69	9	**19**	**30**	**34**
Fond Saint Jacques 4 (total)	2.96	30	**49**	**79**	**93**

Table 9 : Peak flows calculations in Fond Saint Jacques

The concentration times are extremely short: less than 15 minutes to reach the first houses of the community. Catchment areas are very small but situated in heavy rainfall zone of the island and with very steep slopes. This is why the peak flows are very high regarding the contribution areas.

3.4 Hurricane Tomas analysis

For Hurricane Tomas, no hourly data is available at the rain gauges. Only daily rainfalls have been measured at the Union and Hewanorra aiport stations (respectively 539 mm and 593 mm).

The weather radar of Météo France located in Martinique (Le Diamant, lat = 14.501389, lon = -61.017500 °) covers the island St. Lucia.

The radar data were acquired from Météo France for the entire event. These radar rainfall data are estimated with the "Panther" algorithm (Météo France), they are raw data with a number of prior corrections: removing ground echo, correction of masks... These data are not calibrated with respect to rain gauges. These data are provided with a timestep of 15 minutes and on a pixel grid of 1 km^2.

For this episode, it appears that the South part of the St Lucia Island was incorrectly seen by the radar. According to Météo France, this would be the impact of winds that could strengthen the rains in the lower layers of the atmosphere, not seen in full by the radar beam in the southern part of the island. This phenomenon is not systematic, and for other episodes, the island is entierely "seen" by the radar (episode in December 2013 for example).

For Tomas event, a general correction factor of 1.8 should be applied to the raw data provided by the radar. For Soufriere catchment, the coefficient seems to be higher, with a value of 2,2. These coefficients were estimated by comparing the accumulated radar on the pixels corresponding to the rain gauges with the cumulative rainfall at the rain gauge. The correction coefficient has been estimated at four rain gauges stations:

- Union station : radar 300 mm, measured rainfall 549mm
- Forestierre : radar 334mm, measured rainfall 635 mm
- Anse La Raye : radar 225mm, measured rainfall 405 mm
- Desraches : radar 300 mm, measured rainfall 668 mm (this station is very close to the Soufriere catchment).

The rainfall totals were provided by St Lucia MetOffice.

The map of cumulative rainfall data "corrected" by applying a factor of 1.8 to radar data is provided in Figure 22, with the location of the rain gauge stations.

The cumulative rainfall estimated for the Soufriere and Dennery catchments are provided in Table 10, and the maximum values obtained for durations from 15 minutes to 24 hours values.

The 15 minutes hyetographs for the catchments Soufriere and Dennery show the chronology of the Tomas event on both basins.

- For the Dennery catchment: the average cumulative rainfall is estimated to 550 mm. The most intense part of Tomas occurred in the second half of event, after several smaller events that generated a cumulative rainfall of more than 200 mm.
- For the Soufrière upstream catchment (cressland river), the average cumulative rainfall is estimated to 686 mm (cressland river). The most intense part of the event is rather produced in the first part of the event, which brings a cumulative rainfall of 451 mm. The second part of the event produces a cumulative rainfall of 235mm on soil already saturated.
- For the Fond St Jacques catchment, the cumulative rainfall of the event is estimated to 760 mm. The maximum 15 minutes intensities occur in the first part of the event (total 510mm). The second part of the event produces a cumulative rainfall of 250mm and occurs on saturated soils. It also contains intensity peaks.

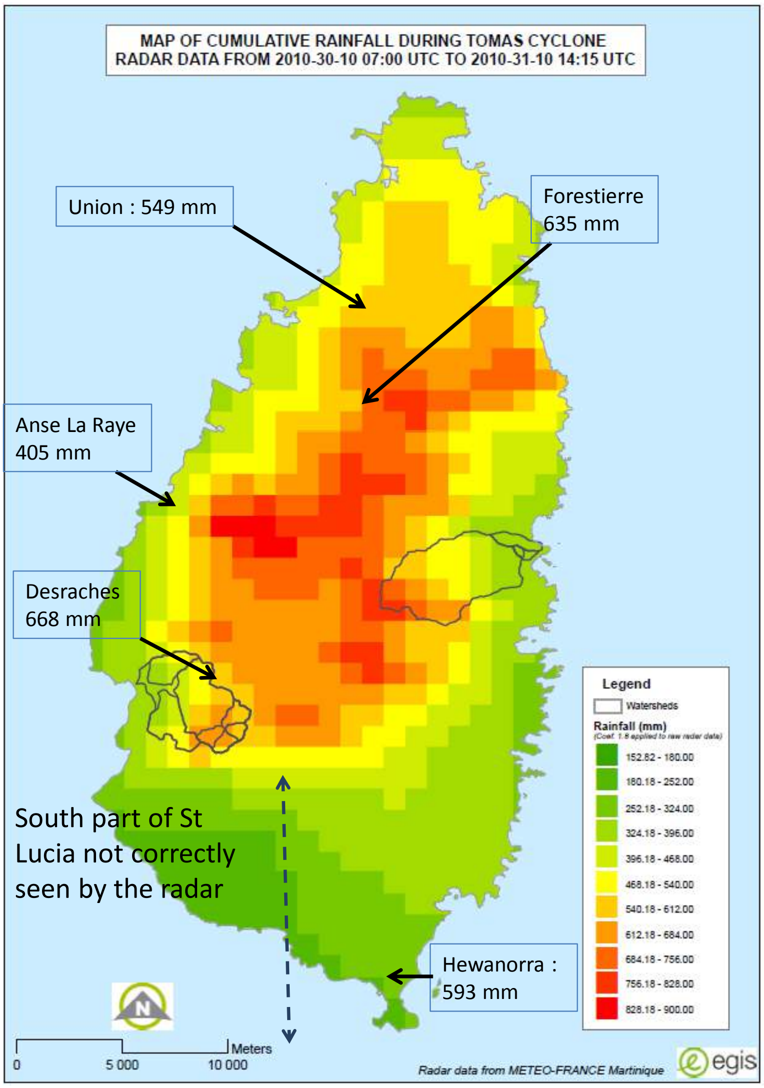


Figure 29 : Map of 24h cumulative rainfall during Tomas cyclone estimated from radar rainfall data

	Maximum average rainfall estimated on the catchment (mm)							
	15 min.	30 min.	1h	2h	4h	6h	12h	24h
Dennery catchment	18	31	52	94	154	214	363	530
Soufriere Fond St jacques	18	34	55	100	180	262	476	739
Soufriere cressland river	20	33	57	103	180	247	447	668
Soufriere sulphur river	19	31	52	90	163	224	387	565
Soufriere Ruby	17	30	53	88	142	186	287	404

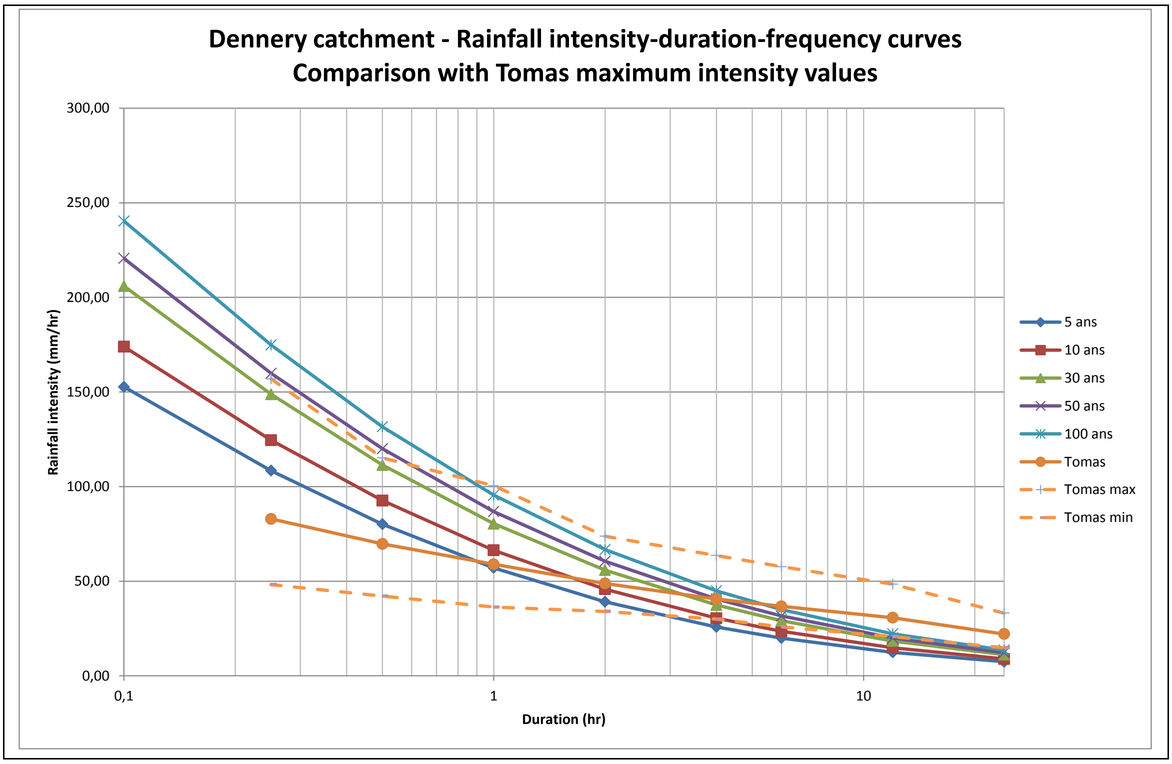
	Maximum rainfall estimated on the catchment on a 1km2 pixel (mm)							
	15 min.	30 min.	1h	2h	4h	6h	12h	24h
Dennery catchment	39	58	100	148	254	346	581	796
Soufriere Fond St jacques	24	43	76	133	214	293	531	802
Soufriere cressland river	27	47	87	137	259	328	531	802
Soufriere sulphur river	29	44	69	123	191	280	517	750
Soufriere Ruby	19	35	59	98	161	202	318	443

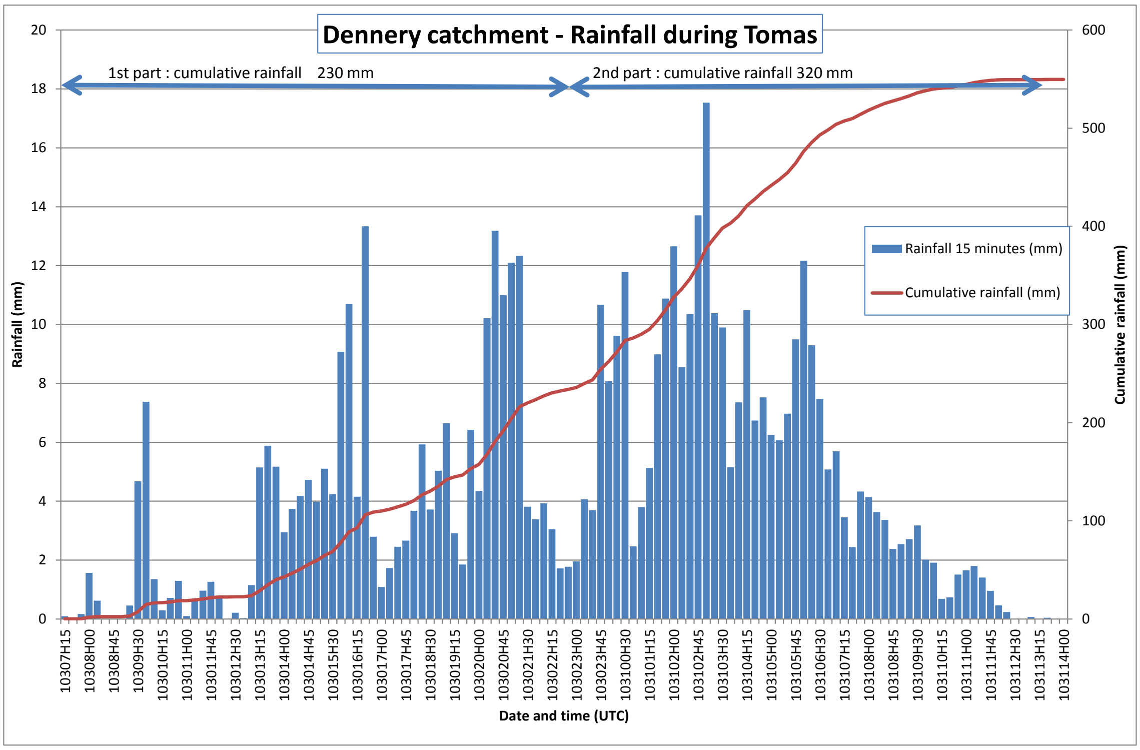
Table 10 : Tomas rainfall estimations

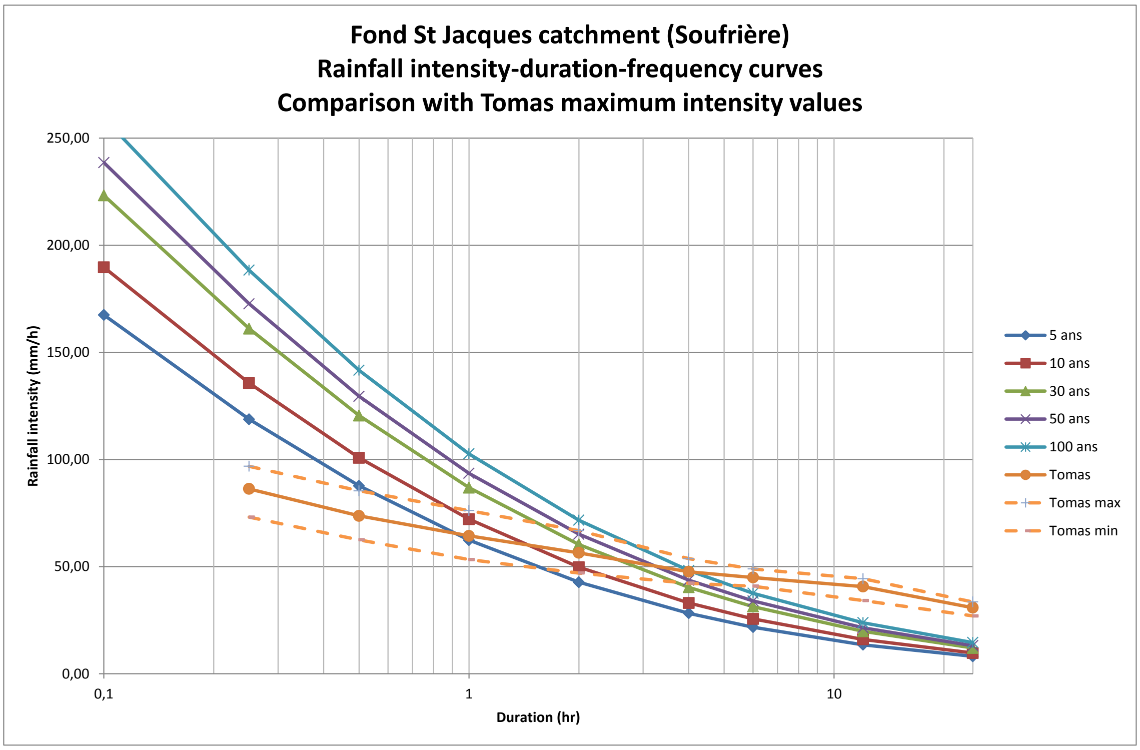
The analysis of maximum values for various durations and comparison with the previously defined characteristic values shows:

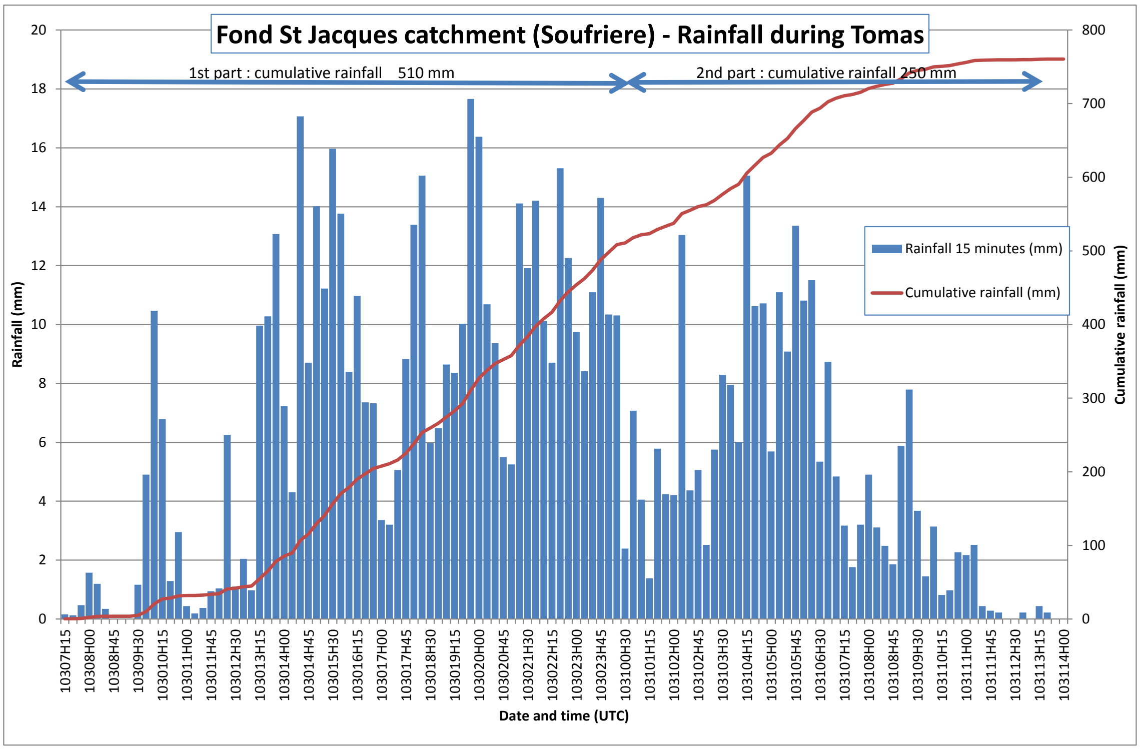
- intensities on short durations with return periods that are not exceptional: the return period of 10 years is reached for the duration 2h for both catchments of Dennery, and Soufriere
- the return period of 50 years is reached for the 4h duration on both catchments,
- the return period of 100 years is exceeded from the 6h duration and beyond for the both catchments The return period exceeds also 100 years for the 24h duration on both catchments.
- The maximum intensity values in the catchment (for a 1km2 pixel) exceeds the return period 30 years from the 15 minutes duration on Dennery catchment and beyond 1h duration on Soufriere catchment.

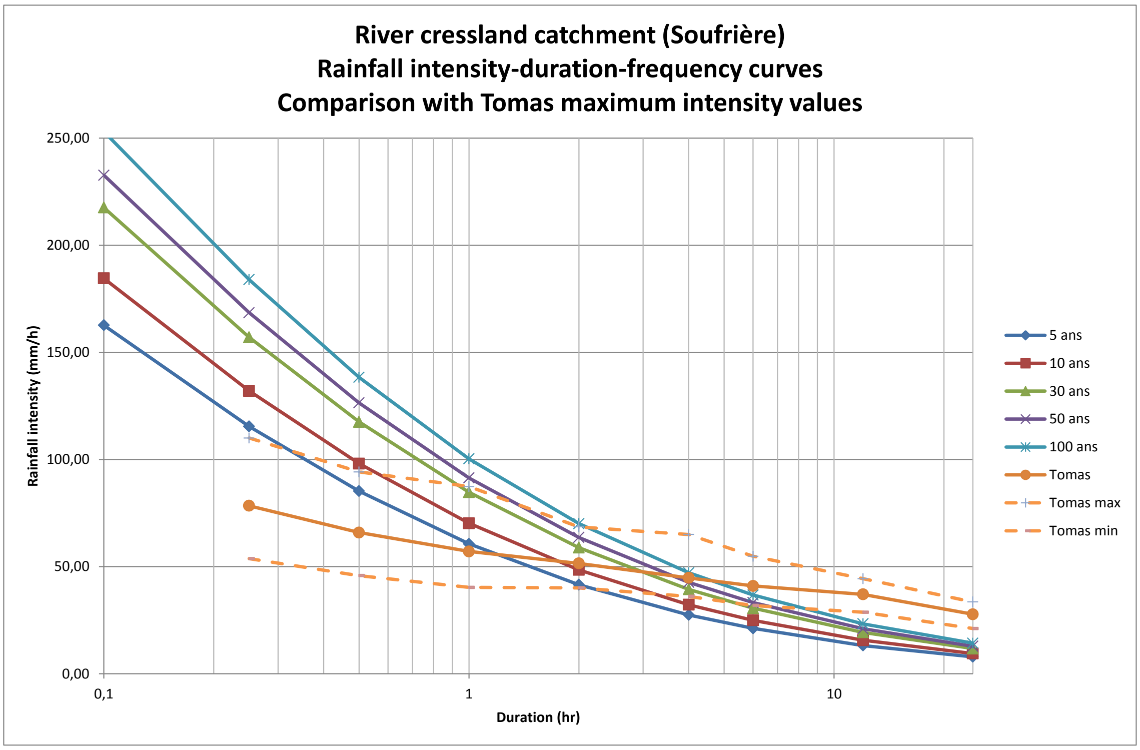
Tomas event is remarkable and exceptional in its cumulative rainfall exceeding the return period of 100 years for duration from 6h on both Dennery and Soufriere catchments. The maximum intensities corresponding to the concentration times estimated for the catchments (2h for Dennery, 1h for Soufriere) have return periods of about 10 years for Dennery and 5 years for Soufriere catchment. However they occur on soils saturated by a cumulative rainfall of about 300 mm at least, probably leading to very high runoff coefficients.

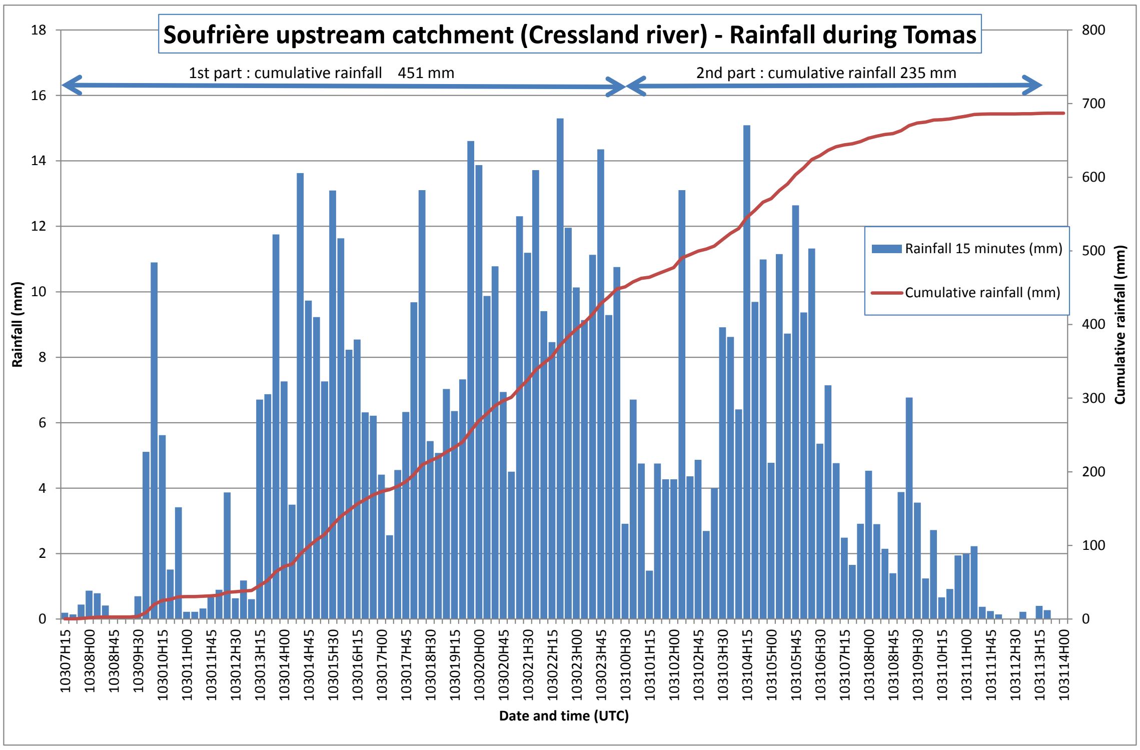

Dennery catchment - Rainfall intensity-duration-frequency curves
Comparison with Tomas maximum intensity values
Rainfall intensity (mm/hr)
300,00
250,00
200,00
150,00
100,00
50,00
0,00
0,1
1
10
Duration (hr)
5 ans
10 ans
30 ans
50 ans
100 ans
Tomas
Tomas max
Tomas min


Dennery catchment - Rainfall during Tomas
1st part : cumulative rainfall 230 mm
2nd part : cumulative rainfall 320 mm
Rainfall (mm)
20
18
16
14
12
10
8
6
4
2
0
Cumulative rainfall (mm)
600
500
400
300
200
100
0
Rainfall 15 minutes (mm)
Cumulative rainfall (mm)
10307H15
10308H00
10308H45
10309H30
103010H15
103011H00
103011H45
103012H30
103013H15
103014H00
103014H45
103015H30
103016H15
103017H00
103017H45
103018H30
103019H15
103020H00
103020H45
103021H30
103022H15
103023H00
103023H45
103100H30
103101H15
103102H00
103102H45
103103H30
103104H15
103105H00
103105H45
103106H30
103107H15
103108H00
103108H45
103109H30
103110H15
103111H00
103111H45
103112H30
103113H15
103114H00
Date and time (UTC)


Fond St Jacques catchment (Soufrière)
Rainfall intensity-duration-frequency curves
Comparison with Tomas maximum intensity values
Rainfall intensity (mm/h)
250,00
200,00
150,00
100,00
50,00
0,00
0,1
1
10
Duration (hr)
5 ans
10 ans
30 ans
50 ans
100 ans
Tomas
Tomas max
Tomas min


Fond St Jacques catchment (Soufriere) - Rainfall during Tomas
1st part : cumulative rainfall 510 mm
2nd part : cumulative rainfall 250 mm
Rainfall (mm)
20
18
16
14
12
10
8
6
4
2
0
Cumulative rainfall (mm)
800
700
600
500
400
300
200
100
0
Rainfall 15 minutes (mm)
Cumulative rainfall (mm)
10307H15
10308H00
10308H45
10309H30
103010H15
103011H00
103011H45
103012H30
103013H15
103014H00
103014H45
103015H30
103016H15
103017H00
103017H45
103018H30
103019H15
103020H00
103020H45
103021H30
103022H15
103023H00
103023H45
103100H30
103101H15
103102H00
103102H45
103103H30
103104H15
103105H00
103105H45
103106H30
103107H15
103108H00
103108H45
103109H30
103110H15
103111H00
103111H45
103112H30
103113H15
103114H00
Date and time (UTC)


River cressland catchment (Soufrière)
Rainfall intensity-duration-frequency curves
Comparison with Tomas maximum intensity values
Rainfall intensity (mm/h)
250,00
200,00
150,00
100,00
50,00
0,00
0,1
1
10
Duration (hr)
5 ans
10 ans
30 ans
50 ans
100 ans
Tomas
Tomas max
Tomas min


Soufrière upstream catchment (Cressland river) - Rainfall during Tomas
1st part : cumulative rainfall 451 mm
2nd part : cumulative rainfall 235 mm
Rainfall (mm)
18
16
14
12
10
8
6
4
2
0
Cumulative rainfall (mm)
800
700
600
500
400
300
200
100
0
Rainfall 15 minutes (mm)
Cumulative rainfall (mm)
10307H15
10308H00
10308H45
10309H30
103010H15
103011H00
103011H45
103012H30
103013H15
103014H00
103014H45
103015H30
103016H15
103017H00
103017H45
103018H30
103019H15
103020H00
103020H45
103021H30
103022H15
103023H00
103023H45
103100H30
103101H15
103102H00
103102H45
103103H30
103104H15
103105H00
103105H45
103106H30
103107H15
103108H00
103108H45
103109H30
103110H15
103111H00
103111H45
103112H30
103113H15
103114H00
Date and time (UTC)

Discharges and hydrographs estimations:

To test and validate hydraulic models, flood hydrographs generated by Hurricane Tomas were estimated. The assumptions used are as follows:

- Runoff coefficient varying from 0,6 at the beginning of event to 0,8 during the event (after a cumulative rainfall of 250 mm)
- synthetic unit hydrograph defined for the estimation of characteristic discharges,
- average hyetograph on the catchment.

3.5 Water level and river discharge data

The WRMA is capable to do courant measurement and is collecting data from gauging and automatic stations.

A few water level gauges with continuing data have been installed in Mabouya, Degios and Canelle.

Unfortunately there is no equipment in the studied areas.

To this date, there is no watershed management plan in Saint Lucia. One Study has been proposed to the World Bank Financial program to provide a general outline of what could be an efficient watershed management plan. Once it will be done, this will have to be applied on one specific watershed to improve it.

Chapter 4. Sea levels

4.1 Objective

Towns in Saint Lucia built in relatively flat stream valleys adjacent to the coast, such as Dennery and Soufriere are areas most susceptible to storm surge and flooding. Those two phenomena are often closely linked.

The objective of this part of the study is to determine extreme sea levels in Soufriere and Dennery bays, in order to model correctly the flooding risk in those 2 towns (see next chapter where the calculated sea levels will be used as downstream condition of the hydraulic models).

4.2 Statistical high sea levels

Under the influence of extreme weather and oceanic conditions, water levels at the coast can increase due to a combination of factors:

- the morphology of the shoreline, called "**site effect**" (average slope of the seabed, exposition / shape of the coastline, etc.), which can enhance or reduce effects of weather conditions ;
- weather conditions (wind, pressure, waves), i.e.:
    - a depression or low-pressure weather system will cause a rise in water level. This phenomenon is called the "inverse barometer effect". A decrease of 1hPa is roughly equivalent to an increase in water level of 1cm.
    - wind blowing for a sustained amount of time on the sea surface toward the coast (resp. the sea) will push water toward the shore (resp. the sea) and increase (resp. decrease) water level at the coast ; this phenomenon is called "wind setup";
    - wave conditions: by approaching the coast and breaking, the waves transfer their energy in the water column, causing an elevation of mean sea level of up to several tens of centimeters ; this phenomenon is called "wave setup";

  The water level rise caused by wind and barometric pressure effects is called "meteorological, or **storm surge**".

The mean sea level during a storm results from all of these contributions, together with the **astronomical tide** (less than 0.5m in the area).

To obtain the maximum level reached by the sea, the swash must also be taken into account, that is to say the ebb and flow of waves across the beach or protection works. **Run-up** is the term for the maximum altitude reached by the swash. These phenomena cause coastal flooding, which can be increased by the erosion of the coastline, caused by wave action.

This maximum dynamic level is however mostly considered to estimate wave overtopping and induced flooding over coastal protections.

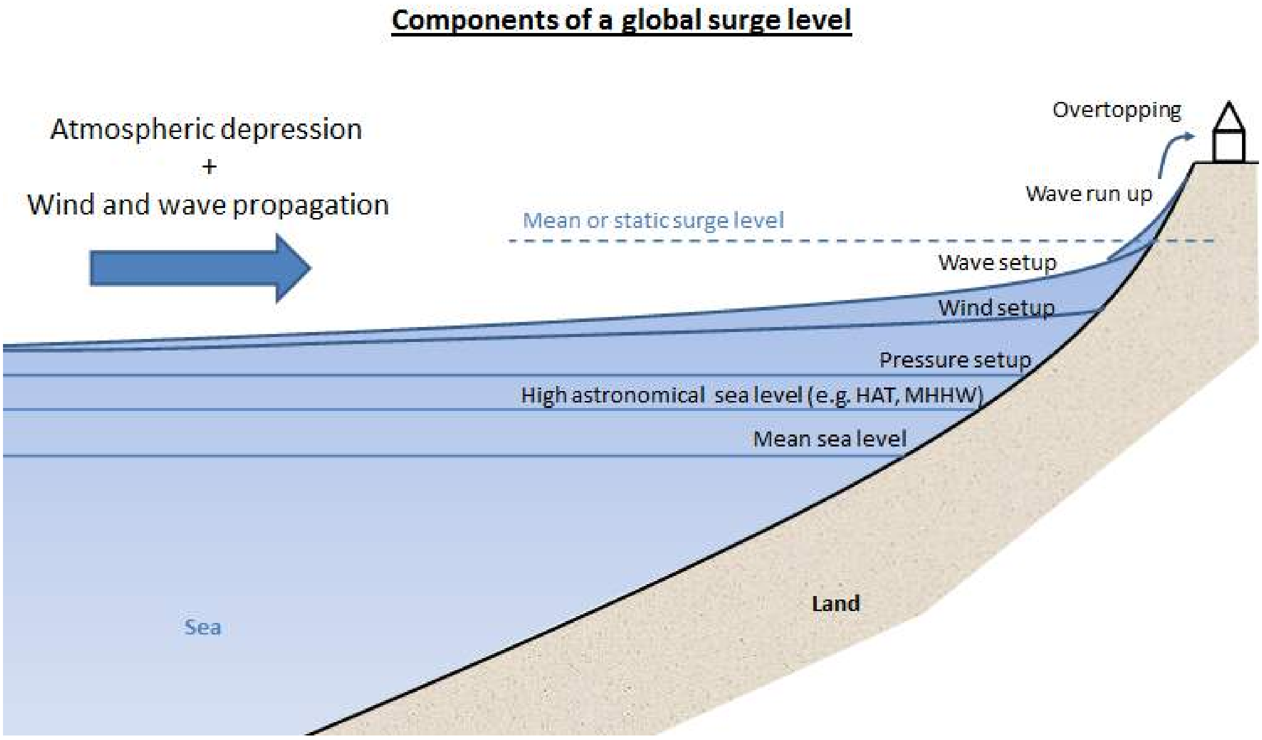


Figure 30 : component of a global surge level

Storm surge values given in the following tables must be considered with caution due to relative lack of data on Saint-Lucia Island in bibliography, and to the fact that wave setup has been estimated via empirical formulas.

The CDMP (Caribbean Disaster Mitigation Project) study provides values of waves and surges, the latter one including atmospheric surge and wave set-up (but not wave run-up). However, statistic values of wave height presented below are similar on the western (Atlantic) and on the eastern (Caribbean) coasts. These results may not be completely realistic because the Atlantic shore is usually more exposed to cyclonic wind and waves than the Caribbean one.

Storm surge values given by the CDMP seem to be underestimated as well.

That is why the highest values of the table below should be considered.

Wave set-up is here roughly estimated using a simple 10% ratio of the significant wave height in open water. Values up to 30% of the wave height can also be found in scientific literature depending on bathymetry and wave steepness. These wave setup values therefore need to be considered with caution.

Furthermore, only the static wave setup has been considered, while dynamic wave setup, corresponding to surf-beat, could influence additional sea level oscillations, with periods in the range of about 1 min.

Sea level rise (SLR) due to global warming has not been integrated here. To model long term events we advise to integrate this component. According to the last IPCC report, published in 2013, the mean sea level due to global warming is forecasted to rise between 0.26 m and 0.82 m from now to 2100.

Finally, mean sea level can vary slightly during a year and from one year to another on account of:

- Seasonal variation of surface temperature.
- Seasonality of trade winds (impacts tropical ocean essentially)
- Spatial and temporal variation of oceanic circulation (oceanic gyres)

Sea level oscillation of about 10 to 50 cm may appear at mid-term in the West Indies. No precise data however has been found.

Figure 31 : Location of wave recorder buoys used

Acronyms:

Hs: Significant height

MSL: Mean Sea Level

SLR: Sea Level Rise (due to global climate warming)

4.2.1 Soufriere Bay

Table 11: Surge and extreme seawater levels estimated at Soufrière Bay for 10-yrs to 100-yrs return periods (no SLR considered)

Return period (yrs)	Hs deep water (m)		Wave set-up (m) *	Storm surge (m) [4]	**Total surge (m) estimated from previous columns ****	**Total surge (m) Values given by CDMP [2]**	**Astronomical tide MHHW (m/MSL) [3] ******	**Site effect (m)**	**Estimated extreme water level (m/MSL) (no SLR considered)**
	Values provided by MF [1]	Values provided by CDMP [2]							
10		3.5	0.35			0.1	0.18	0.3	**0.6**
50	7	5.3	0.53 to 0.70	< 0.25 ***	< 0.95	0.4	0.18	0.4	**1.0 to 1.5**
100	8	6.0	0.60 to 0.80	< 0.30 ***	< 1.10	0.5	0.18	0.5	**1.2 to 1.8**

[1] Météo-France cyclonic waves study (Martinique Island) – Météo-France (MF)

[2] Atlas of Probable Storm Effects in the Caribbean Sea – Caribbean Disaster Mitigation Project (CDMP) – OAS/USAID

[3] Environmental Impact Assessment : Gros Islet and Soufriere – Smith Warner International for USAID – 2001

[4] Evaluation of the risk due to hurricane storm surge in the french West Indies – Météo-France – 2002

* Value calculated as 10% of significant wave height in open water

** Sum of the wave set-up and meteorological surge given in column 4 and 5 of this table

*** The values reported in the table are representative of the cyclonic surges which can be expected along the Caribbean coast of the Martinique Island, which is more exposed to cyclonic events than St-Lucia. These values are therefore probably greater than those which can be expected at Soufriere Bay.

**** From measurements in the Port of Castries

4.2.2 Dennery Bay

Table 12: Surge and extreme seawater levels estimated at Dennery Bay for 10-yrs to 100-yrs return periods (no SLR considered)

Return period (yrs)	Hs deep water (m)		Wave set-up (m) *	Storm surge (m) [4]	**Total surge (m) estimated from previous columns ****	**Total surge (m) Values given by CDMP [2]**	**Astronomical tide MHHW (m/MSL) [3] ******	**Site effect (m)**	**Estimated extreme water level (m/MSL) (no SLR considered)**
	Values provided by MF [1]	Values provided by CDMP [2]							
10		3.5	0.35			0.1	0.18	0.3	**0.6**
50	9	5.3	0.53 to 0.9	< 0.30 ***	< 1.20	0.5	0.18	0.4	**1.1 to 1.8**
100	10	6.0	0.60 to 1.0	< 0.40 ***	< 1.40	0.6	0.18	0.5	**1.3 to 2.1**

[1] Météo-France cyclonic waves study for La Trinité district (Martinique Island) - Part 1 – Météo-France

[2] Atlas of Probable Storm Effects in the Caribbean Sea – Caribbean Disaster Mitigation Project (CDMP) – OAS/USAID

[3] Environmental Impact Assessment : Gros Islet and Soufriere – Smith Warner International for USAID – 2001

[4] Evaluation of the risk due to hurricane storm surge in the French West Indies – Météo-France – 2002

* Value calculated as 10% of significative wave height in open water

** Sum of the wave set-up and meteorological surge given in column 4 and 5 of this table

*** The values reported in the table are representative of the cyclonic surges which can be expected along the Atlantic coast of the Martinique island, which is more exposed to cyclonic events than St-Lucia. These values are therefore probably greater than those which can be expected at Dennery Bay.

**** From measurements in the Port of Castries

4.3 Tomas high sea levels

In this part we have estimated the maximum seawater level which could occur during Hurricane Tomas.

Table 13: Hurricane Tomas - Metocean data measurements available

Hurricane Tomas	**Maximum Wind speed (m/s) [1]**			**Mini. Atmospheric pressure at sea level [1] (mb)**		**Wave height (m) [2]**	
						Sainte-Lucie	**Fort-de-France**
Hewanorra Airport ST LUCIA	Date - time (UTC)	Sustained	Gust	Date -time (UTC)	Pressure	Hm0/ Hmax	Hm0 / Hmax
	30/10/2010 19:15	39.61	43.73	30/10/2010 19:26	997.8	5.0 / 7.3	NA / 1.8

[1] Tropical Cyclone Report: Hurricane Tomas – National Hurricane Center – March 2011

[2] Meteorological consequences, on Martinique Island, of Tomas hurricane, on October 30th and 31th 2010 – Météo-France

* No data available on the sea water level and cyclonic surge on sites

Waves heights recorded during this hurricane reached a significant wave height of 5.0m and a maximum one of 7.3m at Saint-Lucia offshore buoy (see figure above), which should roughly corresponds to a 50-years return period event (according to CDMP and MF data available, presented in Tables 1 and 2).

Wind intensity reached a maximum of about 40 m/s, which also should roughly corresponds to a 50-years return period event (according to CDMP).

The global surge that occurred during this hurricane can therefore be estimated to be representative of a 50-years return period surge.

Given this, the extreme sea level reached during this event can be estimated to the corresponding values reported in the tables before, ie:

- **1.1 m to 1.8 m above mean sea level at Dennery Bay,**
- **1.0 m to 1.5 m above mean sea level at Soufriere Bay.**

4.4 Conclusion

The extreme sea water levels in Dennery bay and Soufriere bay in **actual climate conditions are**:

Actual Extreme sea levels	Dennery Bay	Soufriere Bay
10 years	0.6 m	0.6 m
50 years	1.8 m	1.5 m
100 years	2.1 m	1.8 m
TOMAS	Around 1.8 m	Around 1.5 m

Table 14: Extreme sea water levels

To model long term event for the structural mitigations measures dimensioning, we propose to add the sea level rise due to global warming: between + 0.26m and +0.82m in 2100.

Chapter 5. Bathymetrical and topographical survey

To complete and update available topographical data, in order to permit a good hydraulic modelling, we've asked the company Royal Survey Services (RSS) from Vieux-Fort to do the following survey.

The survey was done with a Topcon Hyperplus GPS system, and LEICA 3'' robotic total station, wich allows a precision of 2cm, in 3 dimensions.

The numeric files (Autocad files) of the survey are given to the client.

The bathymetrical survey is the river channels survey.

The topographical survey is the plain survey.

5.1 In Dennery

- 24 cross sections (blue lines) ; bathymetrical and topographical
- 3 bridges (blue circles)
- 3 longitudinal profiles of the bottom of the rain drain channels (green lines)
- 1 longitudinal profile of the left embankment of the Mole river (green dashed line)
- 4 highest water levels during Tomas (yellow stars)

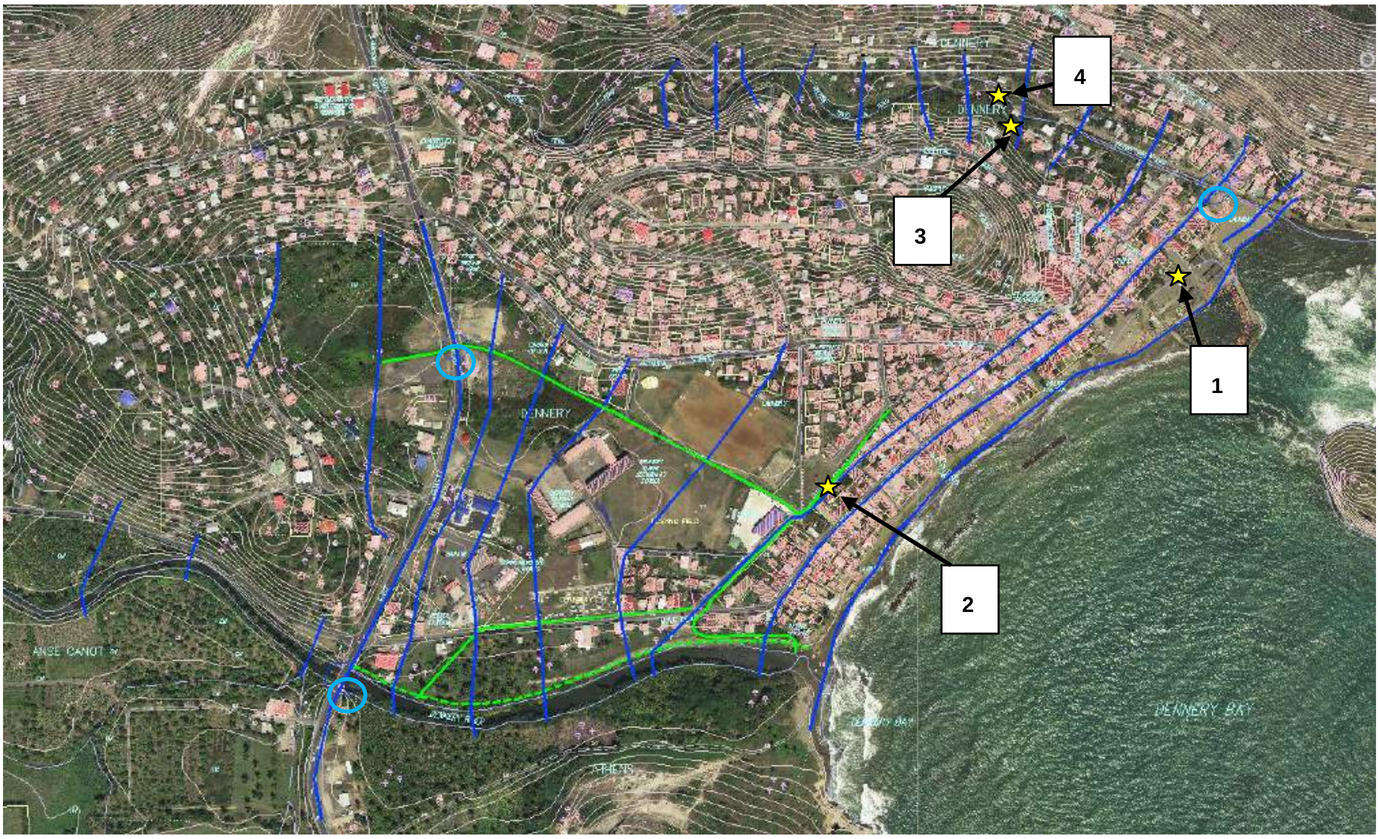


Figure 32 : topographical survey in Dennery

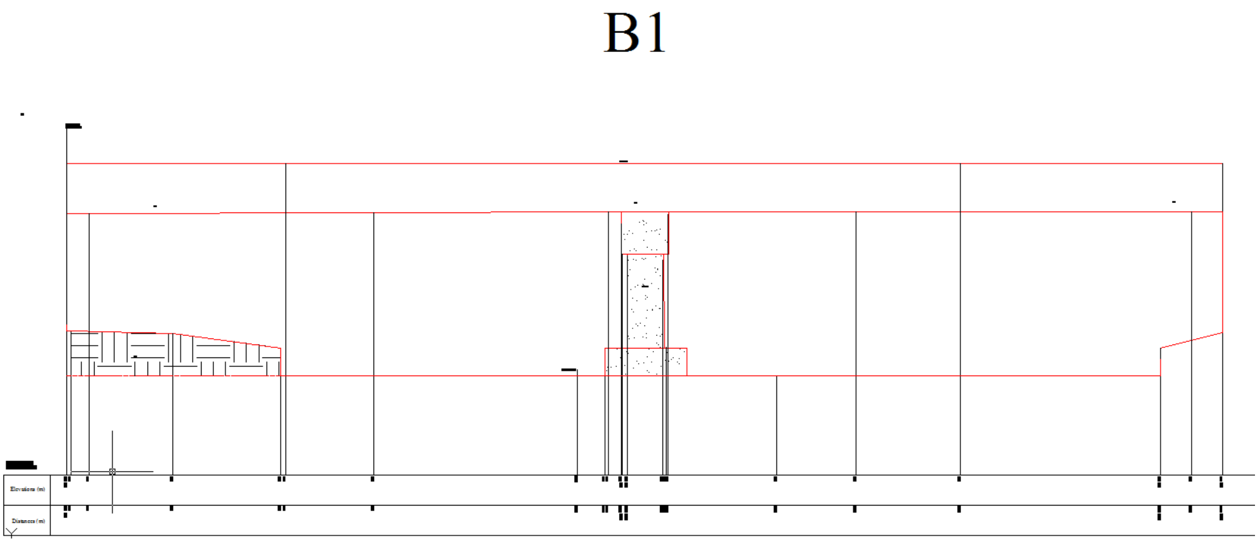


Figure 33 : Example of a bridge survey: the Mole river (main river) bridge

The highest Tomas level are given in the table below. They have been measured after local testimonies. The difficulty of that survey was that Tomas was 3 years before, ans all the physical traces were errased (all the town was rebuilt ans cleaned) so the testimonies were not very precise. Only the points # 1 and 3 were precise (stairs) :

Point #	Quality	Easting	Northing	Elevation (m)
1	Precise	520299.0639	1537813.816	1.92
2	Not precise	519917.3727	1537576.055	3.03
3	Precise	520094.0874	1537968.178	2.51
4	Not precise	519531.5041	1537428.258	3.43

Table 15 : Tomas highest water levels in Dennery

5.2 In Soufriere

- 21 cross sections (blue lines), bathymetrical and topographical
- 3 bridges (blue circles)

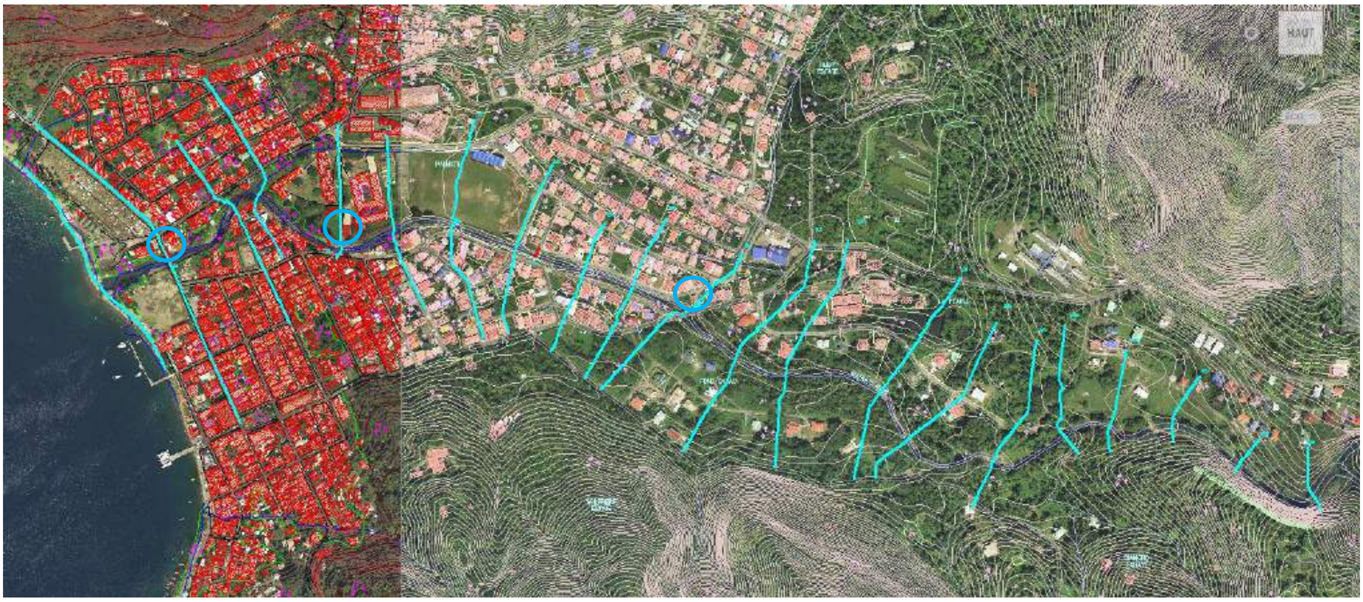


Figure 34 : topographical survey in Soufrière

There are no precise highest Tomas level in Soufriere. The difficulty was that Tomas was 3 years before, ans all the physical traces were errased (all the town was rebuilt ans cleaned) so the testimonies were not precise.

5.3 In Fond Saint Jacques

- 13 cross sections (red lines)
- 2 bridges (blue circles)
- 4 highest water levels during Tomas (yellow stars)

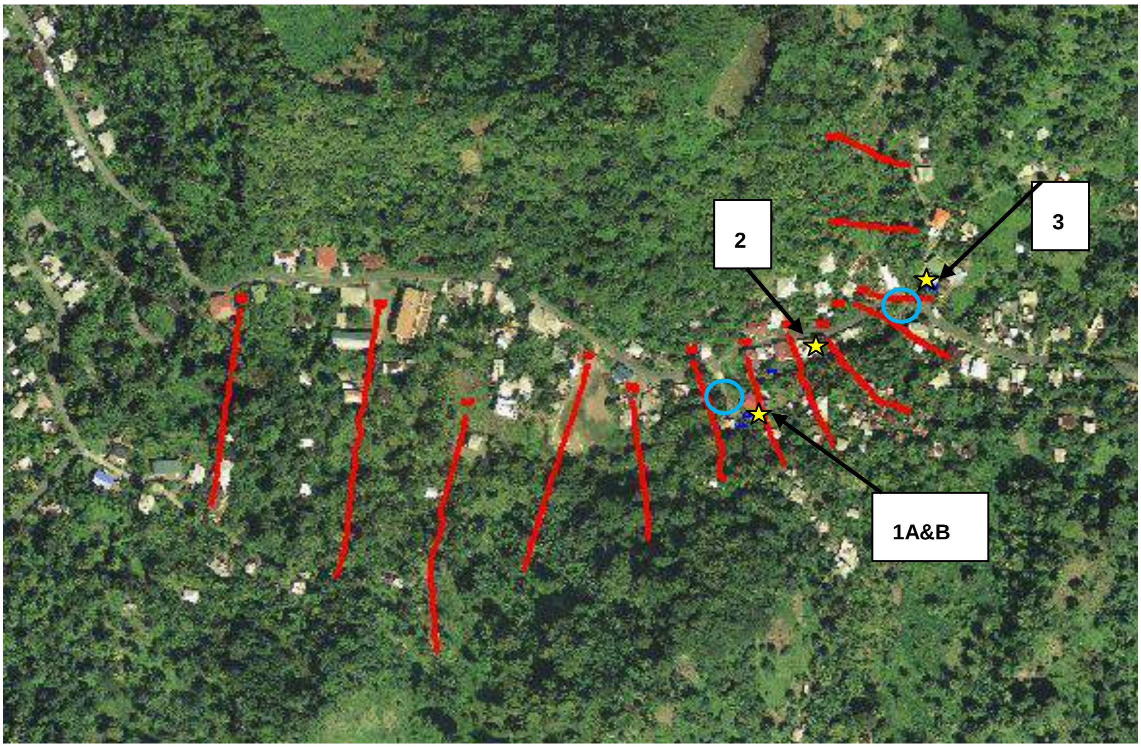


Figure 35 : topographical survey in Fond St Jacques

The highest Tomas level are given in the table below. They have been measured after a field survey. Here the measurements are precise because the traces of dirt and mud on walls all still visible even after 3 years. Houses had been abandoned, neither cleaned nor rebuilt.

Point Name	Easting	Northing	Elevation (m)	Description
1A	505589.1534	1529297.916	272.82	Mud Level
1B	505591.9538	1529305.296	273.44	Dirt Level
2	505610.6007	1529337.128	273.92	Mud Level
3	505725.3986	1529396.521	279.93	Dirt Level

Table 16 : Tomas highest water levels in Fond St Jacques

Chapter 6. Hydraulic modeling

6.1 The software used for the modeling

Flood risk analysis requires the implementation of an hydraulic software model, covering all the studied areas.

- In Dennery and Soufriere a bi-dimensional model
- In Fond Saint Jacques a one-dimension model

The model aims to characterize flow conditions under actual site conditions and to characterize the impact of the floods on the study area.

Every model requires a detailed topography integrating all river beds, hydraulic structures and flood plains on the studied area, seen in the chapter 3.

The modeling will be realized with a **bi-dimensional flows modeling software INFOWORKS-ICM 1D and 2D**

The INFOWORKS RS model is based on the resolution of the full St-Venant equations:

$$\partial S/\partial t + \partial Q/\partial x = q$$

Continuity equation – volume conservation

$$\partial Q/\partial t + \frac{\partial (Q^2/S)}{\partial x} = -gS\left(\frac{\partial Z}{\partial x} + J\right)$$

Dynamic equation – Movement quantity conservation

Solving these equations requires empirical laws regarding head losses, which are established by experiments for linear flows (e.g. Manning/Strickler or Chézy formulas, weirs laws, etc.)

Z	water surface level
Q	flow

a	inflows or losses per m²
x	abscissa
S	wet section
J	hydraulic head gradient

The model solves the full St-Venant equations using the Preissman 4-points scheme, which is stable across a wide range of flow conditions.

The sketching of the study area relies on a database comprising a series of cross sections and profiles along structures such as bridges, weirs, culverts…

This database allows establishing maps of areas liable to flooding, in order to optimize the outlets of hydraulic structures and their associated protections, as well as analysing the functioning of unidirectional and complex hydraulic systems.

Modeling with a bi-dimensional model is justified to precisely represent the flows in the area study.

The meshing model will be adapted to the study area configuration, and is built to take in account flows particularities (obstacles, embankments, infrastructures, topographical discontinuities…)

The interest of the bi-dimensional modeling with this software is the flexibility in the meshing construction: the mesh size can vary and adapt to constraints.

The meshing density results from constraints of flow representation (narrowing in infrastructures), from topography and bathymetry, as well as the required precision

InfoWorks 2D combines a number of distinctive features:

Analysis and prediction of potential flood extent, depth and velocity

Comprehensive functionality to completely model the interaction of surface flows with floodplain structures

Fully integrated 2D modeling environments

Multiple surface mesh design optimizes modeling flexibility and accuracy

Multiple results views, both static and animated

Uses 2D finite volume methods to solve the shallow water flow equations

The software produces water levels at the centre of each mesh cell and velocities across each of the cell faces.

6.2 Dennery modeling: construction and calibration

Dennery modeling is a made with:

- The ravine Trou à l'Eau, the Central drain and the Mole river channels in one dimension, which allows specific modeling of hydraulic structures,
- Connected in the plain, modeled in two-dimension (mesh).

The river channels are constructed with the bathymetric survey data (see previous chapter). The mesh is constructed with the digital field model, based on the topographical data. The maximum size of a mesh is 100 m^2, and there is a mesh every 10cm of height variation.

The Dennery model parameters are shown in the table below and in the following figures.

	Name	**Lenght (Km)**	**Number of cross sections**	**Number of hydraulic structures**	**Mesh number**	**Mesh maximum size (m^2)**	**Terrain-sensitive meshing**	**Maximum height variation for the meshing (m)**
Dennery	**Ravine Trou à L'Eau**	0.75	16	1	173723	100	yes	0.1
	Central drain	0.937	14	1				
	Mole River	0.88	18	1				

Table 17 : Dennery modeling parameters

The calibration of the model parameters (roughness coefficient) was based on Tomas event high water levels survey.

Point #	Quality	Survey water Elevation (m)	Model water Elevation (m)	Difference (m)
1	Precise	1.92	1.93	+0.01
2	Not precise	3.03	2.50	-0.53
3	Precise	2.51	2.47	-0.04
4	Not precise	3.43	2.57	-0.86

Table 18 : Dennery calibration

This table shows that the testimonies # 2 and 4, identified as not precise, couldn't been reach with the model. For the number 4 in particular, we think that the water level measured is due to the local runoff (from the ill) and not to the ravine Trou à l'Eau overflow.

At the contrary, the calibration is very good where the testimonies were precise.

Moreover, the movie of the flood (given to the Client) shows what had been described to us during the field survey: the water coming from the central drain and the overflow of the Mole river dike just after the main road bridge, which filled the Dennery plain with water that couldn't evacuate properly into the sea.

In conclusion, the model is well calibrated on Tomas event.

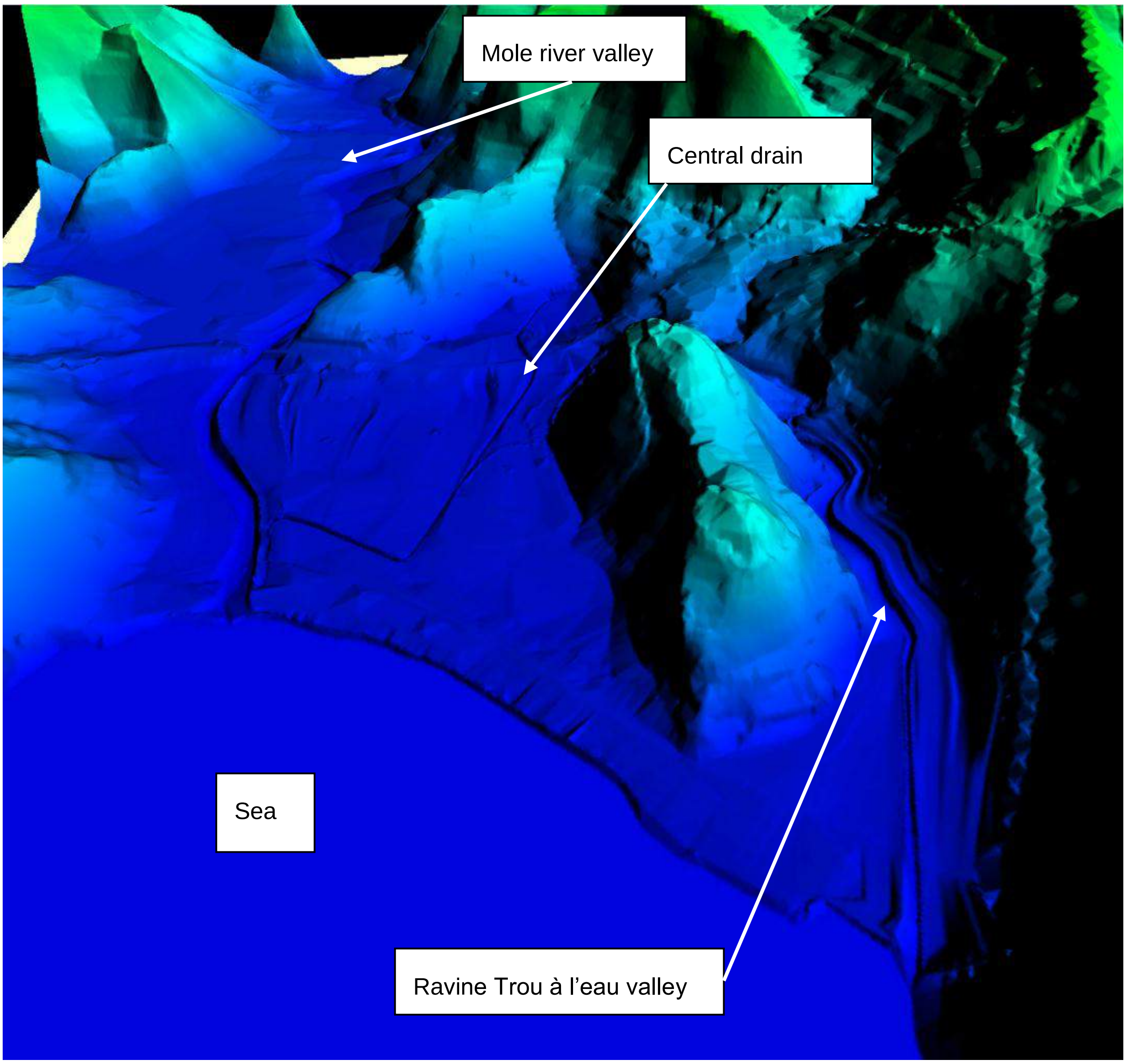


Table 19 : 3D view of Dennery – construction of the digital field model

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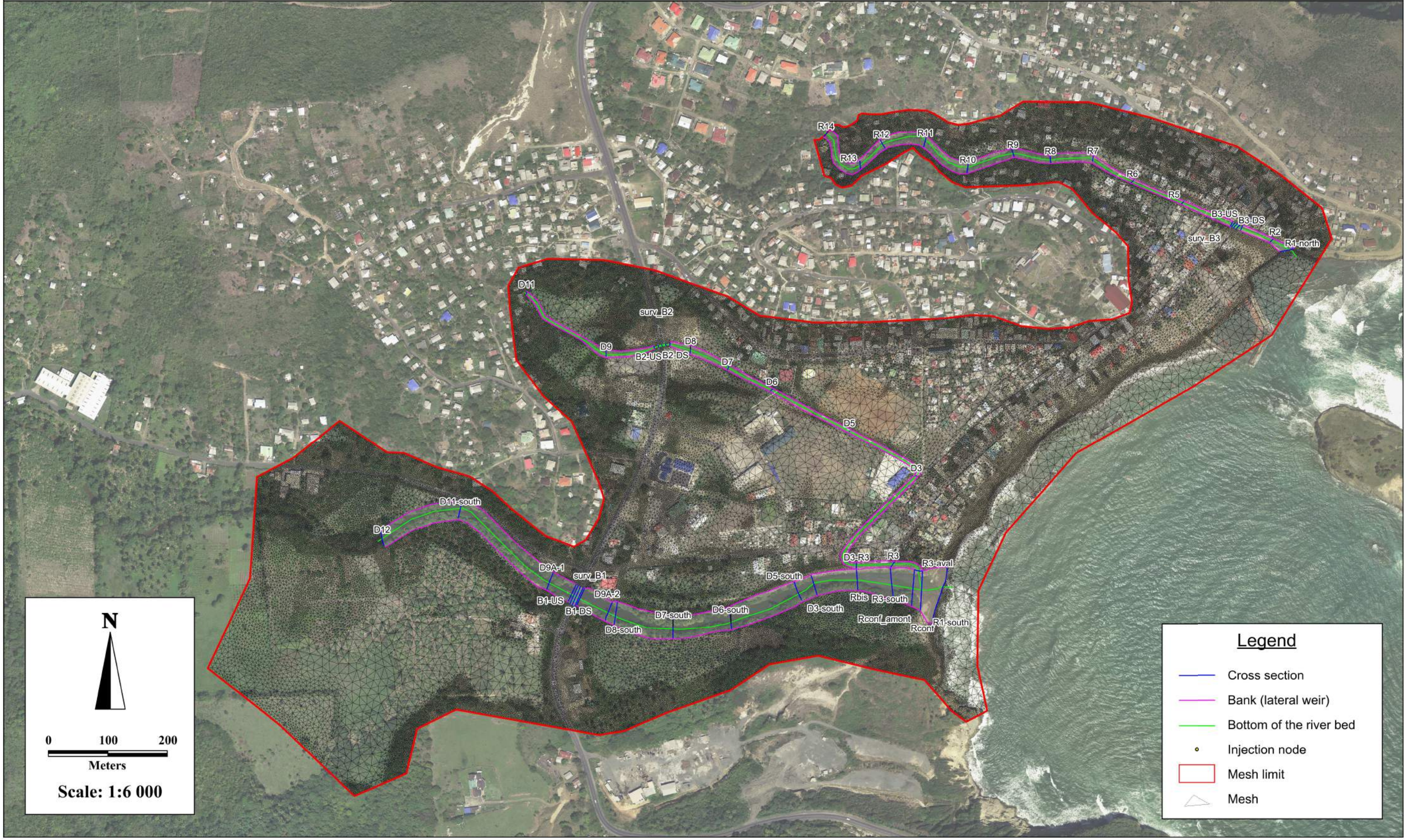
Hydraulic assessment for flood risk assessment in Soufriere, Fond St Jacques and Dennery

Dennery modeling : construction



6.3 Soufriere modeling: construction and calibration

Soufriere modeling is a made with:

- the Soufriere river channel in one dimension, which allows specific modeling of hydraulic structures,
- Connected in the plain, modeled in two-dimension (mesh).
- The flow coming from the tributary “Ruby” is modeled directely in the bi-dimensional area (injection node at the limit of the model at beginning of Soufriere housing area).
- The flow coming from the tributary ”Sulfur Spring” is added directely in the main river.

The river channels are constructed with the bathymetric survey data (see previous chapter). The mesh is constructed with the digital field model, based on the topographical data. The maximum size of a mesh is 100 m², and there is a mesh every 25cm of height variation. This is why the meshes are smaller on the edge of the model area, when it reaches the hillsides.

The Soufriere model parameters are shown in the table below and in the following figures.

Name	Lenght (Km)	Number of cross sections	Number of hydraulic structures	Mesh number	Mesh maximum size (m^2)	Terrain-sensitive meshing	Maximum height variation for the meshing (m)
Soufrière	2.126	28	2	332455	100	yes	0.25

Table 21 : Soufriere modeling parameters

There is no precise maximum water level recorded in Soufriere, but different testimonies of the hydraulic phenomena:

- 1/ The water came straight in the first bend of the river. A house collapsed, washed away by the flood,
- 2/ Downtown the water overflowed in every band and washed away 2 footbridges (near the football field and near the school)
- 3/ There was between 50cm and 1 meter of water in the school
- 4/ The water rushed down the hospital road (West Quinlan St) directly to the sea, the water reached about 1m in front of the hospital but didn’t get into it.
- 5/ The water from the Ruby tributary spread in a large area flooding the North Est part of Soufriere.

All 2,3,4,5 phenomena had been correctly modeled. Even if the testimonies are not precise, the center town of Soufriere is well calibrated.

The first one couldn't be modeled (the water do not reach the top of the bank (about 1 meter high is missing). This can be explained because it is situated in the natural part of the river (upstream part of the model), and Tomas flood as dug it through its passage. The actual river channel (on which the model is constructed) is larger and deeper than when Tomas has begun, that is why the hydraulic phenomena of the natural part of the river in Soufriere could not been modeled. Tomas flood was a morphodynamic flood.

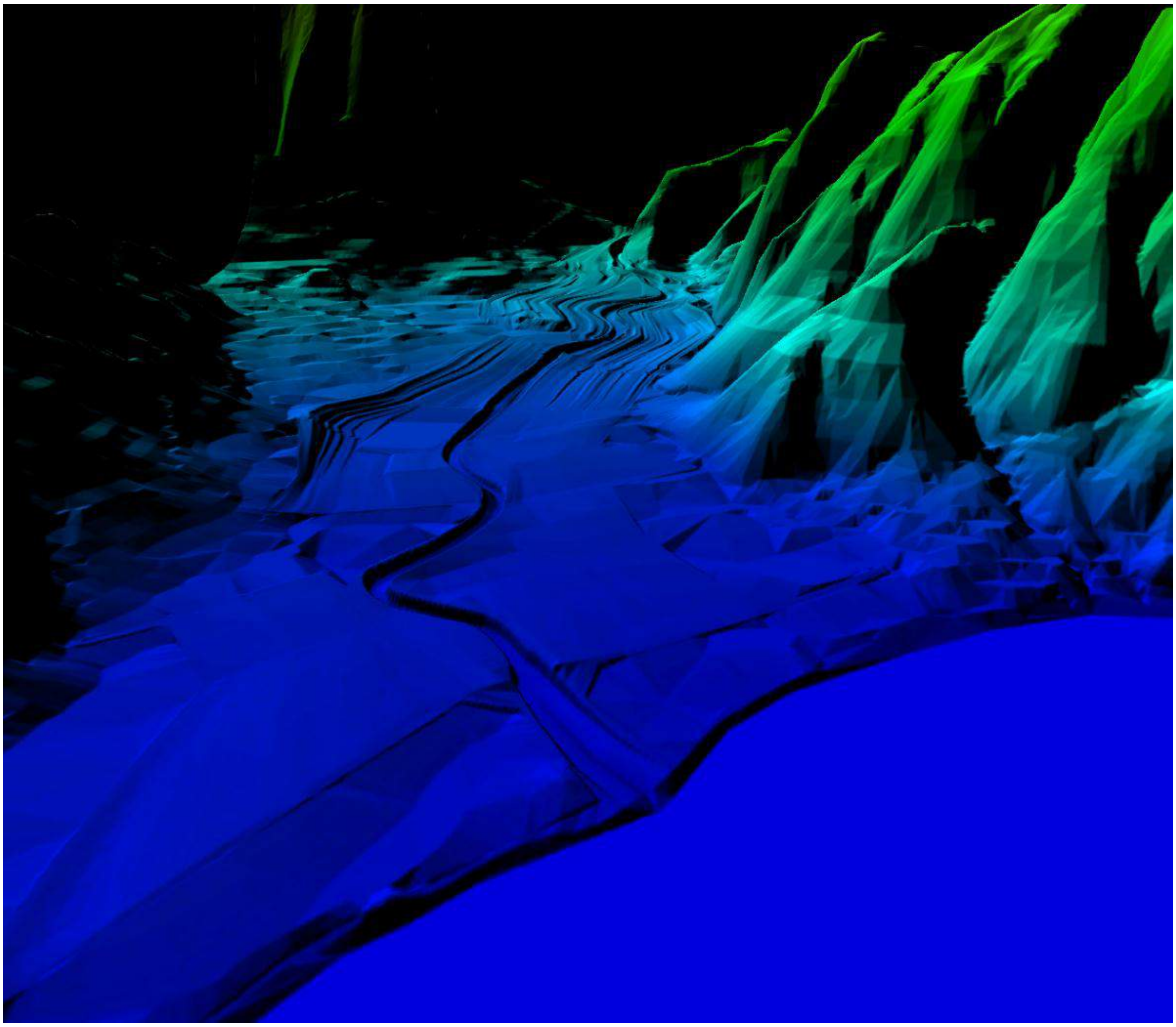


Figure 36 : 3D view of Soufriere – construction of the digital field model

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Hydraulic assessment for flood risk assessment in Soufriere, Fond St Jacques and Dennery

Soufriere modeling : construction

6.4 Fond Saint Jacques modeling: construction and calibration

Fond St Jacques modeling is a made with a one dimension model: there is no complex floodplain to model, this narrow valley can be well modeled in one dimension.

The main valley is modeled with the cross sections surveyed by RSS.

Note that the upstream left tributary had been added to the model after the topographical survey. The cross sections had been built with the island topographical map (1/25000) and field visit and photography's.

The Fond Saint Jacques model parameters are shown in the table below and in the following figures.

Model	Lenght (Km)	Number of cross sections	Number of hydraulic structures
St Jacques (1D)	1.28	27	3

Table 22 : Fond Saint Jacques modeling parameters

A digital field model had been constructed too, in order to calculate in every point of the valley the water depth (difference between the water level and the ground level).

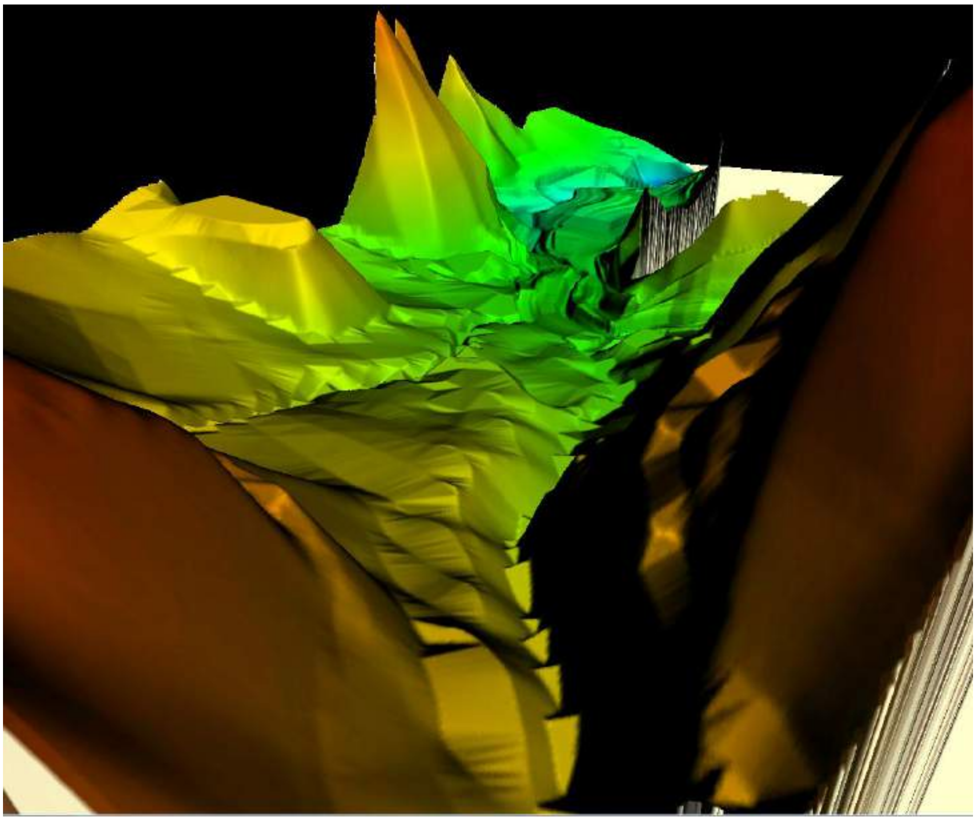

Figure 38 : 3D view of Fond Saint Jacques – construction of the digital field model

As said before, the Fond Saint Jacques particularity is debris flow caused by upstream landslides. Those debris flows can’t be modeled, as it is not possible to determine the amount of cubic meters of debris that could collapse during a rainfall event.

During our field survey, we have seen that a lot of landslides might occur again (lot of very steep and non-vetetalized slopes in the upper catchment).

What can only be said is that Tomas event, with his big landslides, can occur again.

The model is calibrated with the Tomas water/debris levels survey: we increased the peak discharges until the water levels calculated reached the water/debris levels surveyed. This is the only way to produce a good flood/debris exposure map in this community, based on Tomas event.

The calibration of the model parameters (roughness coefficient), based on Tomas event high water levels survey, is very good as shown in table below:

Point #	Quality	Survey water Elevation (m)	Model water Elevation (m)	Difference (m)
1A	Mud level : not applicable	272.82	/	/
1B	Precise	273.44	273.40	-0.04
2	Precise	273.92	273.95	+0.03
3	Precise	279.93	279.89	-0.04

Table 23 : Fond Saint Jacques calibration

The peak discharges had been modeled too, but the flood exposure maps related to those simulations are only due to clear-water overflow (no debris flow taken into account).

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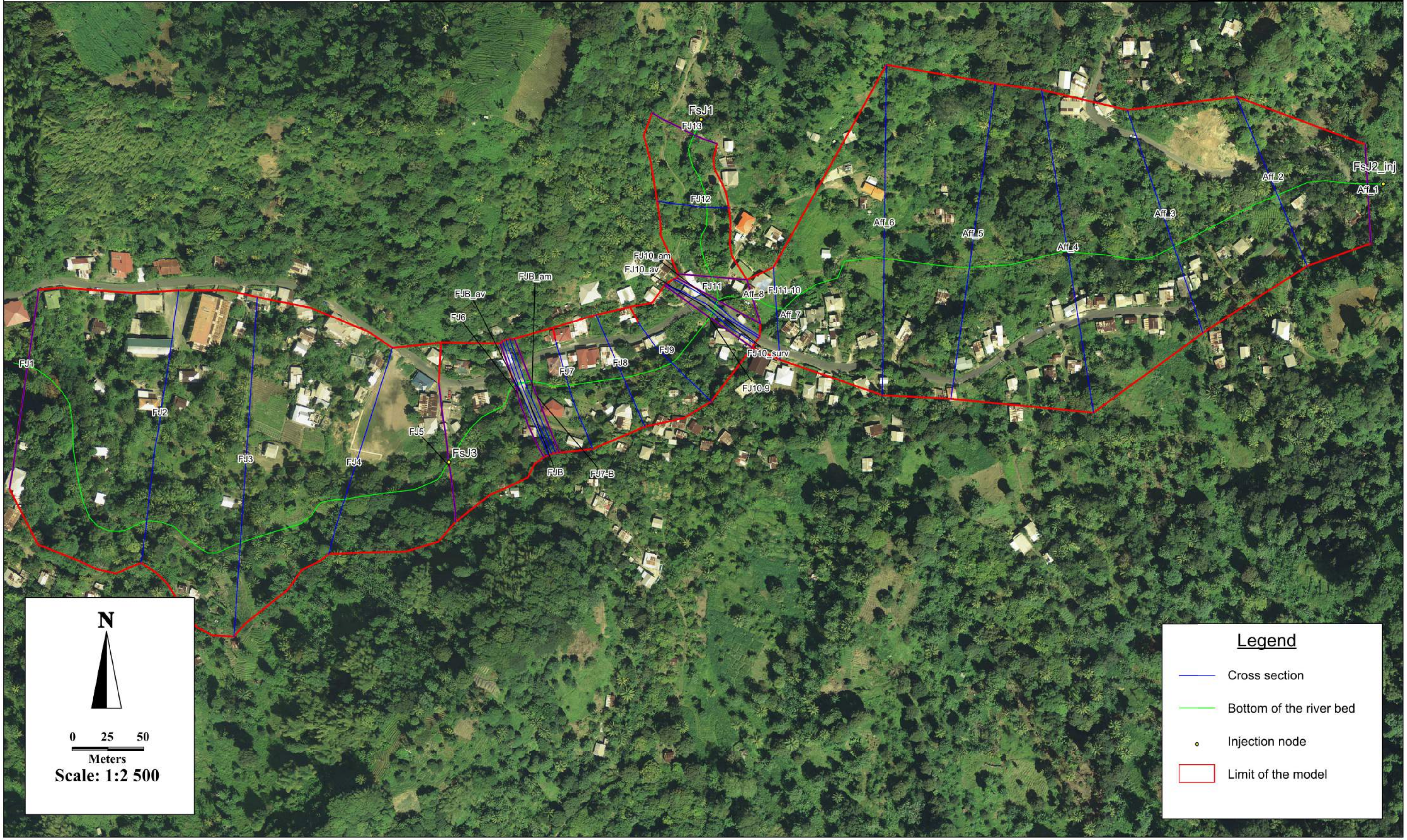
Hydraulic assessment for flood risk assessment in Soufriere, Fond St Jacques and Dennery

St Jaques modeling : construction



Chapter 7. Flood Exposure Maps

The flood expose maps in actual conditions (water maximum levels and velocity) are given in the 3 communities at the end of the report:

- Tomas event,
- 10 years flood,
- 50 years flood,
- 100 years flood.

For each model, upstream conditions are the hydrographs corresponding to the event tested.

Downstream conditions are:

- For Fond saint Jacques: the normal height,
- For Dennery and Soufriere: the 10 years sea levels for 10 and 50 years flood event,
- For Dennery and Soufriere: the 50 years sea levels for 100 years flood event.

7.1 Hydraulic analysis In Dennery

In Dennery, the model shows that the capacity of the rivers and drainage network is less than 1-in-10 return period.

Overflows can be seen:

- **along the ravine Trou à l'Eau** in the lower (straight and concrete) part (about 250m long). The water levels are lower than 50 cm for a 10 years event. This water heights increase with the return period: around 80 cm for 50 years event and more than one meter for 100 years event. More than 50 houses are flooded. The velocity of the water in the upstream part is very high and might cause bank erosion damages.
- In the Dennery plain, **the central drain** can't evacuate the 1-in-10 peak discharge. The upstream wetland is filled with the runoff from the hill and retains the water (the main road is not overflowed for 10 and 50 years events). Downstream the central drain is not big enough and the peak flows cannot be properly evacuated into the sea. The water overflows in the bottom of the valley and is stored in the plain. The front road is built on an elevated embankment which protects the plain from the high sea levels, but keeps the runoff discharges in town, as a storage area. The schools and sport fields are flooded (less than 50 cm for 10 years return period, and between 50cm and one meter for 50 and 100 years events). Moreover, the outlet of the central drain, directly

linked to the Mole river at its mouth, let the water of the Mole river and the sea enter in town. During the flood, when the Mole river and sea levels are high, the outlet let the waters from the river and the sea enter in the town of Dennery, but at the end of the flood this outlet is the only way for the stored waters to be evacuated.

- **The Mole river** actual left bank dike is overflowed for 10, 50 and 100 years events. This dike is not protecting Dennery anymore for flooding (since the breach during Tomas). The water rushes in the central plain of Dennery along the mole road and mixes with the central drain floodplain waters. The only outlet for those waters is the central drain outlet. On the right bank the flooding is severe (this bank has no dike and is very low). The Mole river is taking a larger channel including the right bank (almost 150m large). The velocity of the water is high (about 1m/s). Now this floodway is not constructed, but there is a hotel project on this side of the river that might take into account this particular phenomenon of regular flooding.

7.2 Hydraulic analysis In Soufriere

In Soufriere the upstream part of the model shows that the river is well dimensioned, even for high floods (100 years). This part of the river, with high slopes, had been dug during Tomas flood. The channel is now large and deep enough.

But as the river go downstream, the slope is decreasing. A lot of rocks and stones deposit can be seen in the main channel, silting it (especially inside bends). The river channel is not big enough to evacuate the high floods to the sea without overflow.

The “Ruby” triburay channel is too small to evacuate the 10 years flood event. The water overflows and spreads flooding all the North-Est part of the town.

For the 10 years return period, the overflow is beginning on the left bank, at the level of the sport fields. Unfortunately, the right bank (where the sports fields are) is higher than the left bank: the water rush down on the left bank roads and houses, creating a second arm of the river, until reaching the sea. The center town is flooded with less than 30cm of water.

There is no flood on the right bank of the river.

For the 50 years return period, the overflow is beginning upstream, just after the Sulfur Spring bend. The river is taking a second arm on the left bank. Overflow is seen too at the level of the sports fields, feeding again the left bank flood. The center town left bank is submerged (about 200m large with around 50cm of water)

The river overflows on the right bank too, to a lesser extent, in the sport fields and schools.

For the 100 years return period, the same hydraulic phenomena are seen. The center town left bank is submerged and reach the church (about 230m large with around 1 m of water near the hospital).

The river overflows on the right bank too, to a lesser extent, in the sport fields and schools and downstream until reaching the sea.

7.3 Hydraulic analysis In Fond Saint Jacques

In Fond Saint Jacques the simulations are done only for water flooding. The debris flow is not taken into account.

The model shows that the river bed is correctly dimensioned for the water runoff, there is no flooding in Fond Saint Jacques due only to rain water (if no landslide occurs) for 10 and 50 years events. For the 100 years event, the little bridge is submerged, and the water reaches the main road and the first houses. The bridge of the main road is, at the contrary, well dimensioned.

For the left upstream tributary (river catchment “Fond-St-Jacques 2”), the capacity of the Migny road bridge is 20.5 m^3/s. For memory the sub catchment “Fond-St-Jacques 2” flows are :

$$Q10 = 18\ m^3/s$$

$$Q50 = 28\ m^3/s$$

$$Q100 = 32\ m^3/s.$$

This means that this new bridge is dimensioned for 10 years event, without any upstream landside. For more intense rainfalls or if landslide occurs, the bridge is too small. The water passes over the road and rush downstream on the road flooding the neighbor’s houses.

ANNEXES

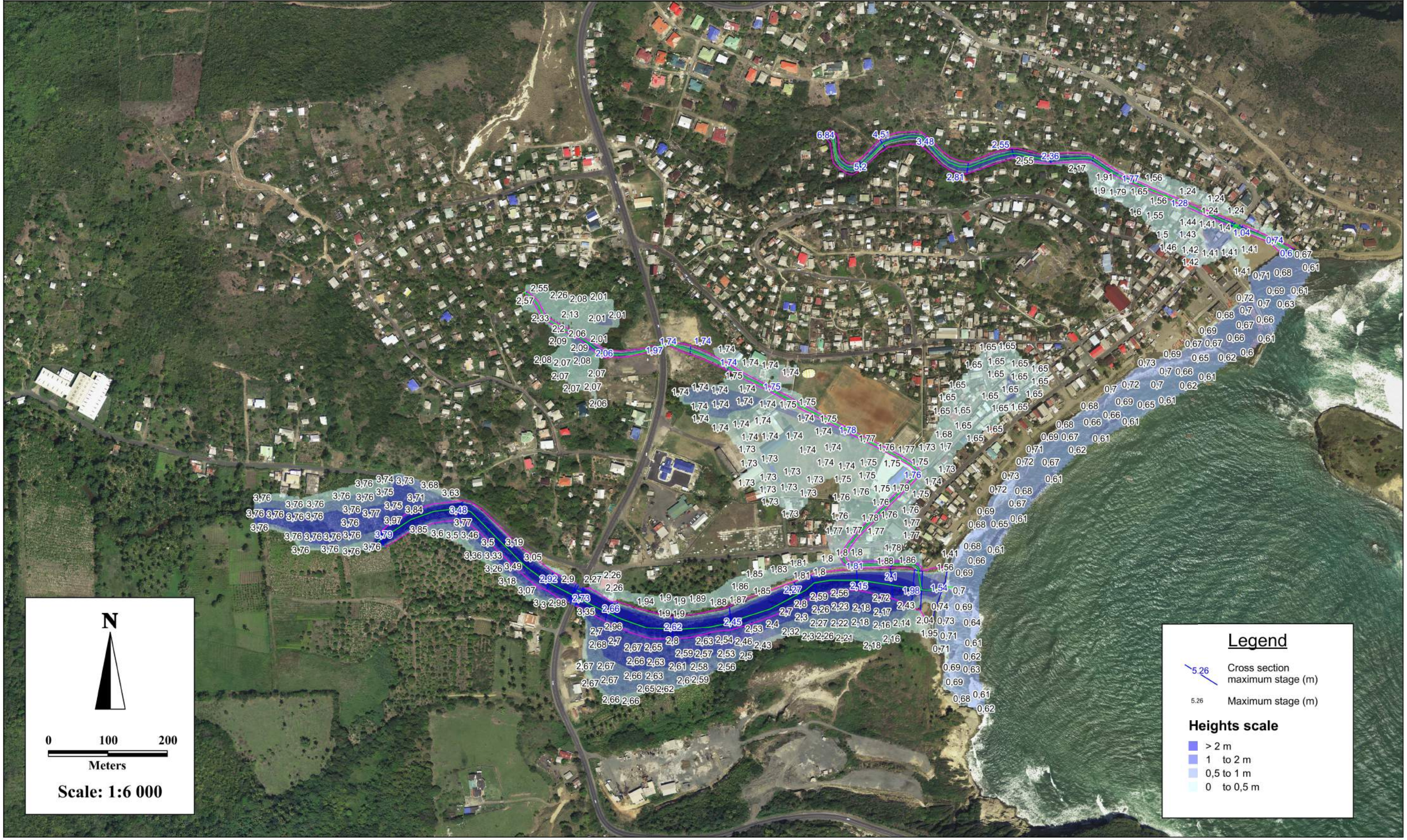
Flood exposures maps (water height and velocity)

Martinique statistical rainfall analysis method

V1_Feb-14

Hydraulic assessment for flood risk assessment in Soufriere, Fond St Jacques and Dennery

Flood exposure map
Water levels for 1-in-10 year flood event



V1_Feb-14

Hydraulic assessment for flood risk assessment in Soufriere, Fond St Jacques and Dennery

Flood exposure map
Water levels for 1-in-50 year flood event

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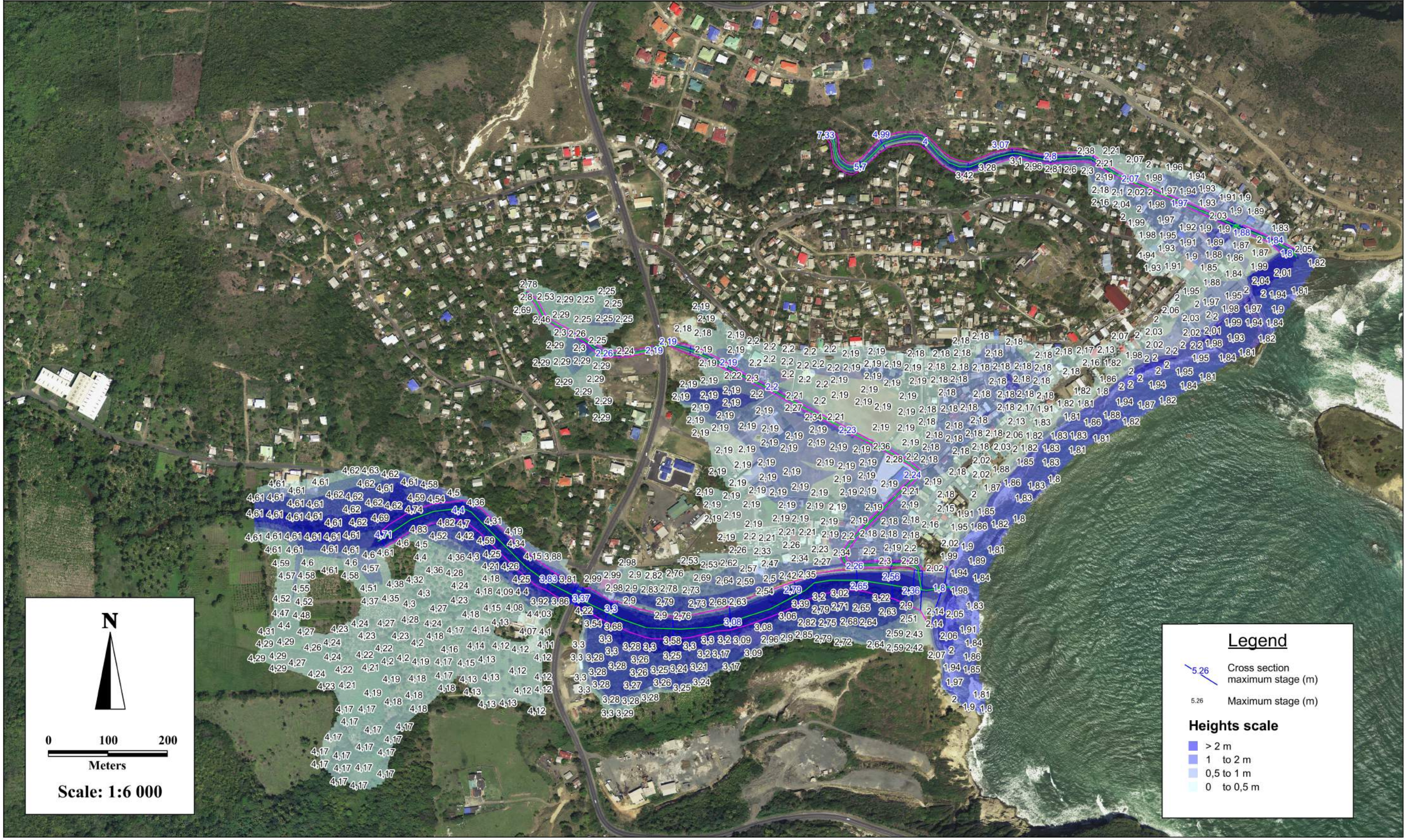
V1_Feb-14

Hydraulic assessment for flood risk assessment in Soufriere, Fond St Jacques and Dennery

Flood exposure map
Water levels for 1-in-100 year flood event



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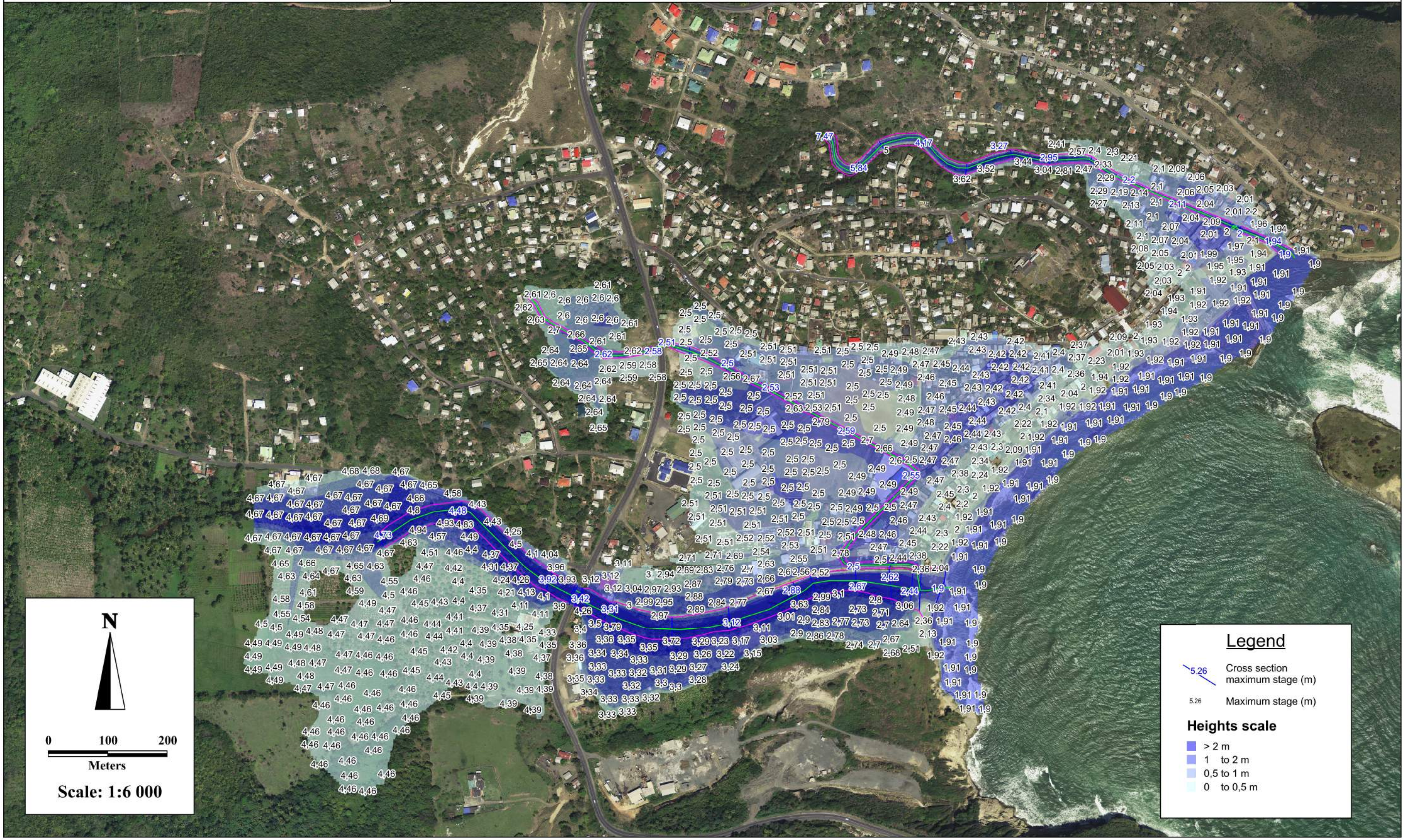
V1_Feb-14

Hydraulic assessment for flood risk assessment in Soufriere, Fond St Jacques and Dennery

Flood exposure map
Water levels for Tomas event



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V1_Feb-14

Hydraulic assessment for flood risk assessment in Soufriere, Fond St Jacques and Dennery

Flood exposure map
Velocity for 1-in-10 year flood event

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V1_Feb-14

Hydraulic assessment for flood risk assessment in Soufriere, Fond St Jacques and Dennery

Flood exposure map
Velocity for 1-in-50 year flood event

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V1_Feb-14

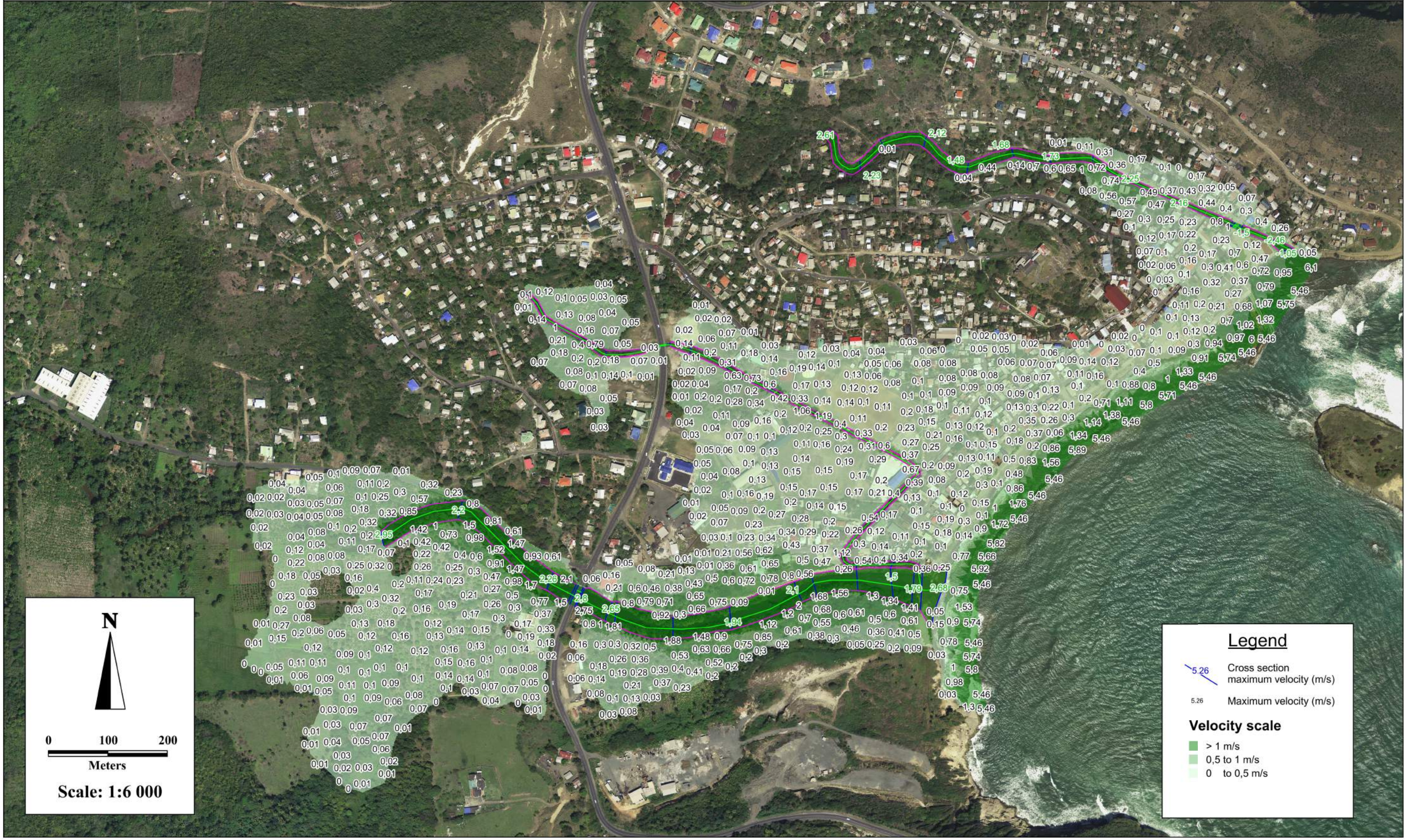
Hydraulic assessment for flood risk assessment in Soufriere, Fond St Jacques and Dennery

Flood exposure map
Velocity for 1-in-100 year flood event

V1_Feb-14

Hydraulic assessment for flood risk assessment in Soufriere, Fond St Jacques and Dennery

Flood exposure map
Velocity for Tomas event



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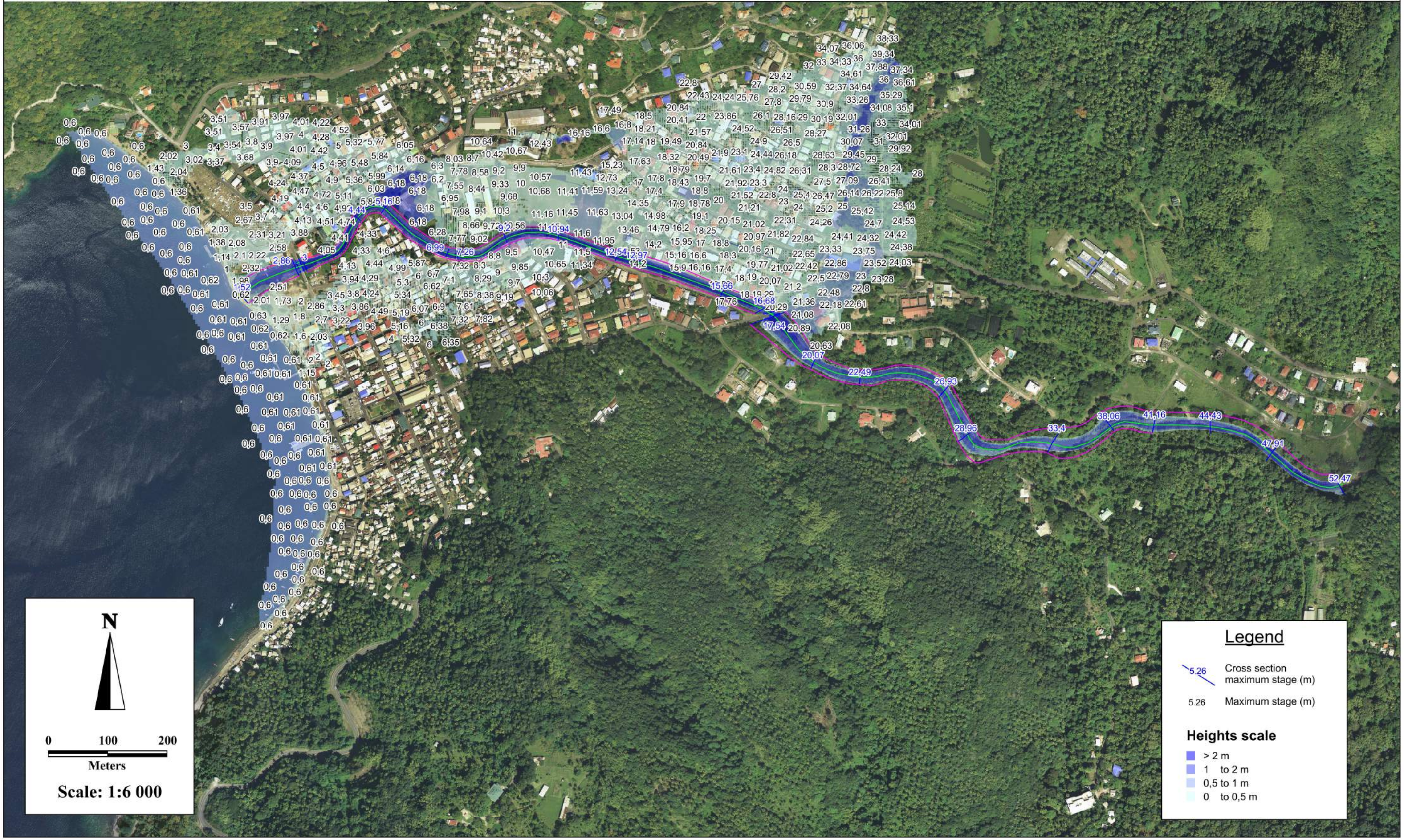
V1_May-14

Hydraulic assessment for flood risk assessment in Soufriere, Fond St Jacques and Dennery

Flood exposure map
Water levels for 1-in-10 year flood event



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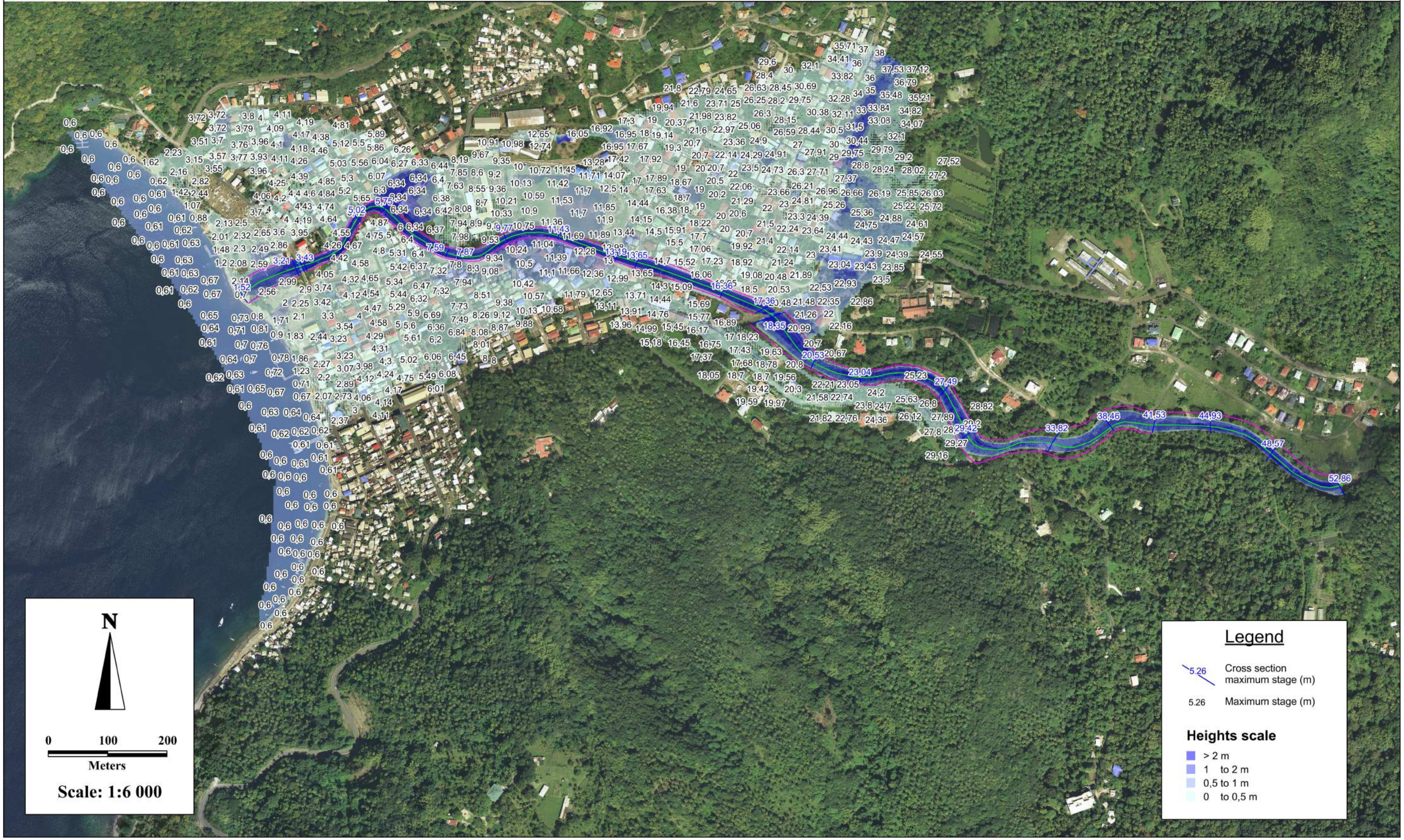
V1_May-14

Hydraulic assessment for flood risk assessment in Soufriere, Fond St Jacques and Dennery

Flood exposure map
Water levels for 1-in-50 year flood event



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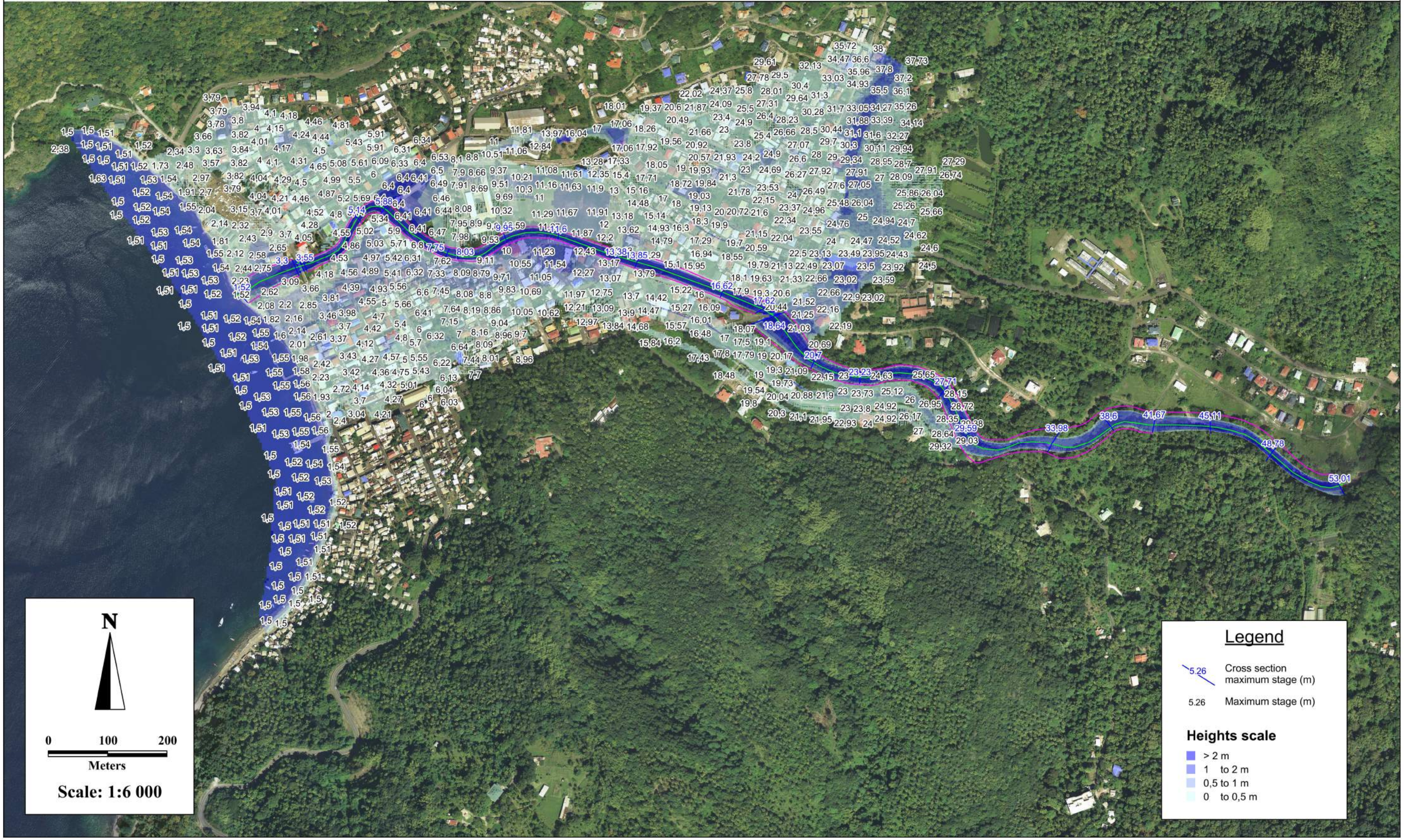
V1_May-14

Hydraulic assessment for flood risk assessment in Soufriere, Fond St Jacques and Dennery

Flood exposure map
Water levels for 1-in-100 year flood event



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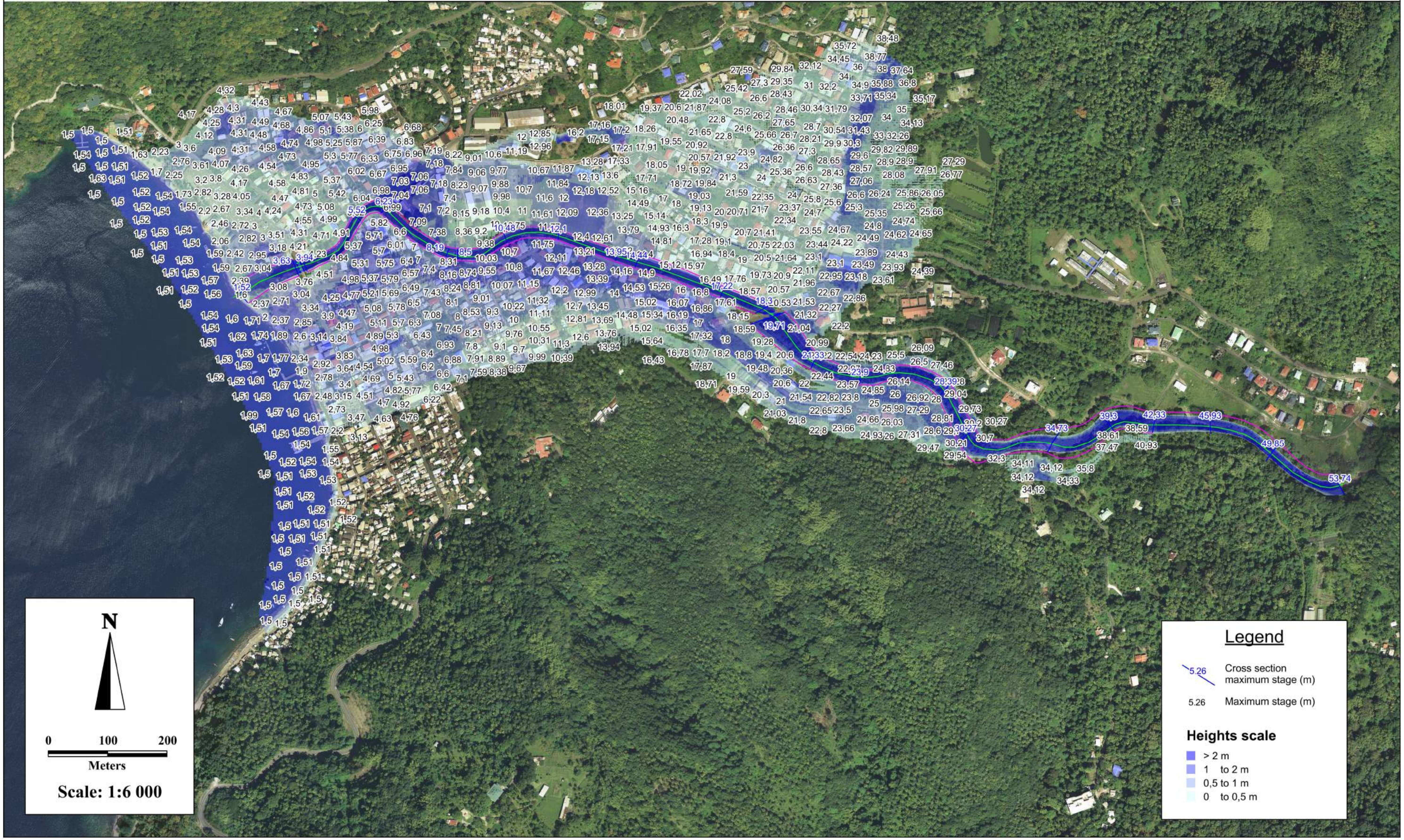
V1_May-14

Hydraulic assessment for flood risk assessment in Soufriere, Fond St Jacques and Dennery

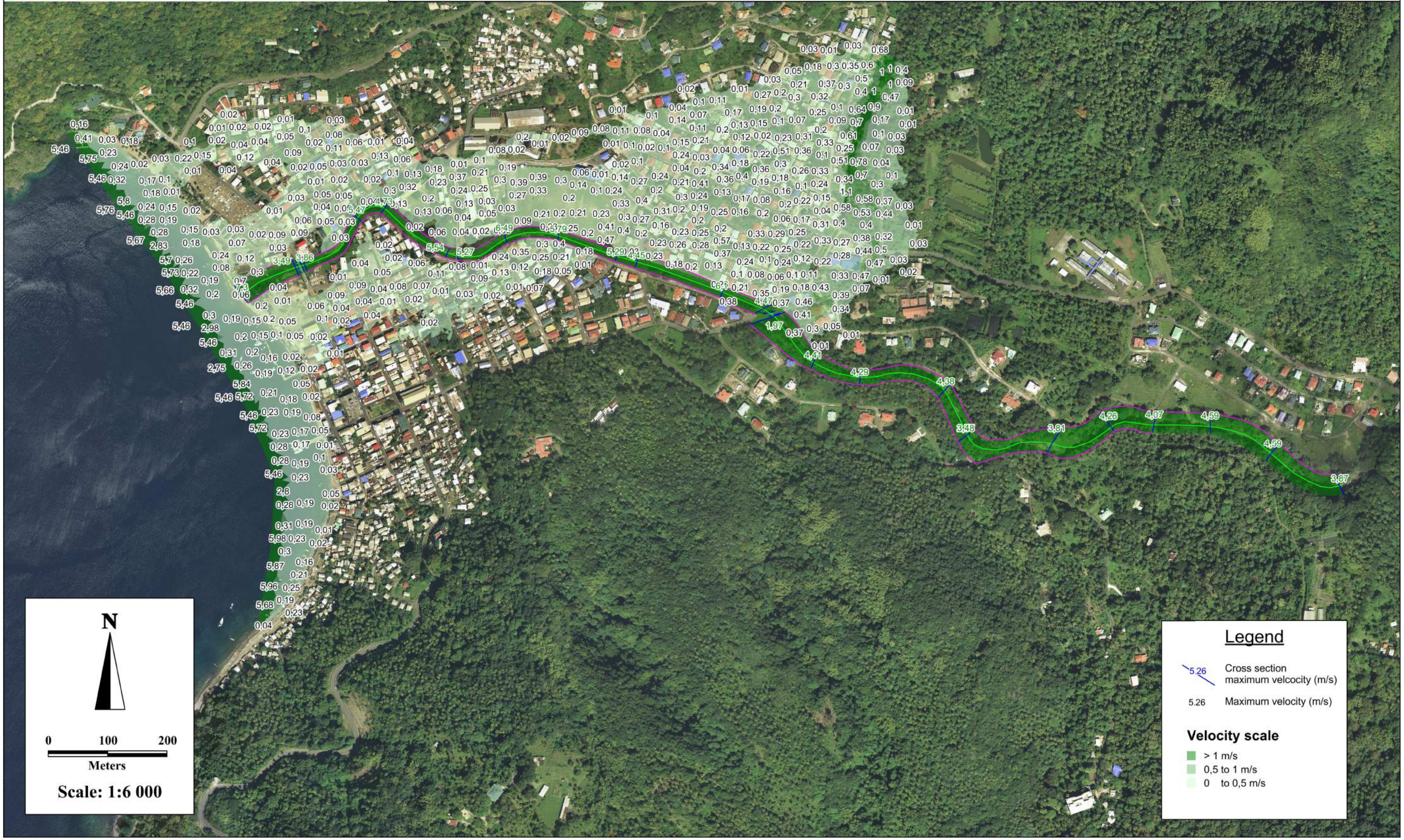
Flood exposure map
Water levels for Tomas event



V1_May-14

Hydraulic assessment for flood risk assessment in Soufriere, Fond St Jacques and Dennery

Flood exposure map
Velocity for 1-in-10 year flood event



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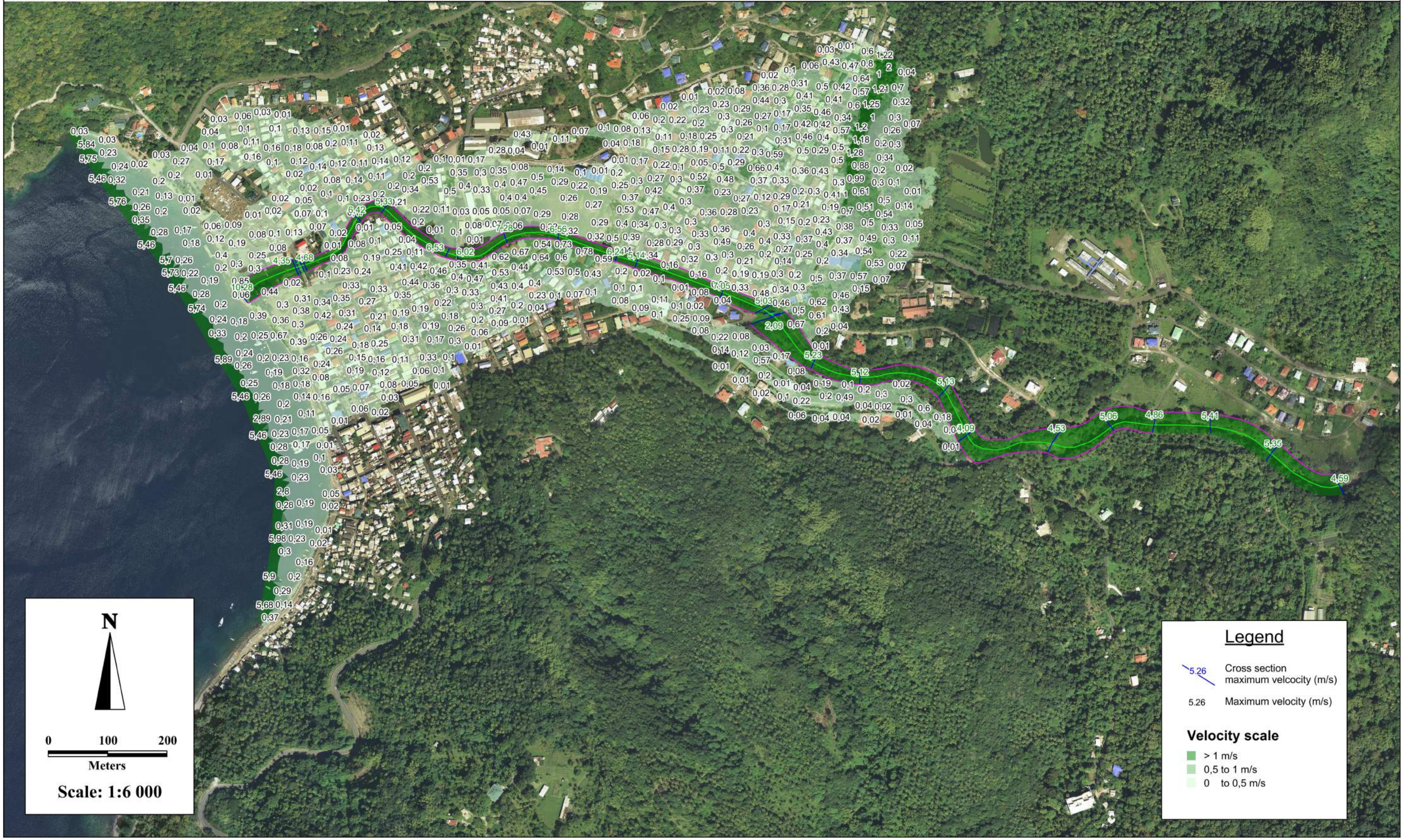
V1_May-14

Hydraulic assessment for flood risk assessment in Soufriere, Fond St Jacques and Dennery

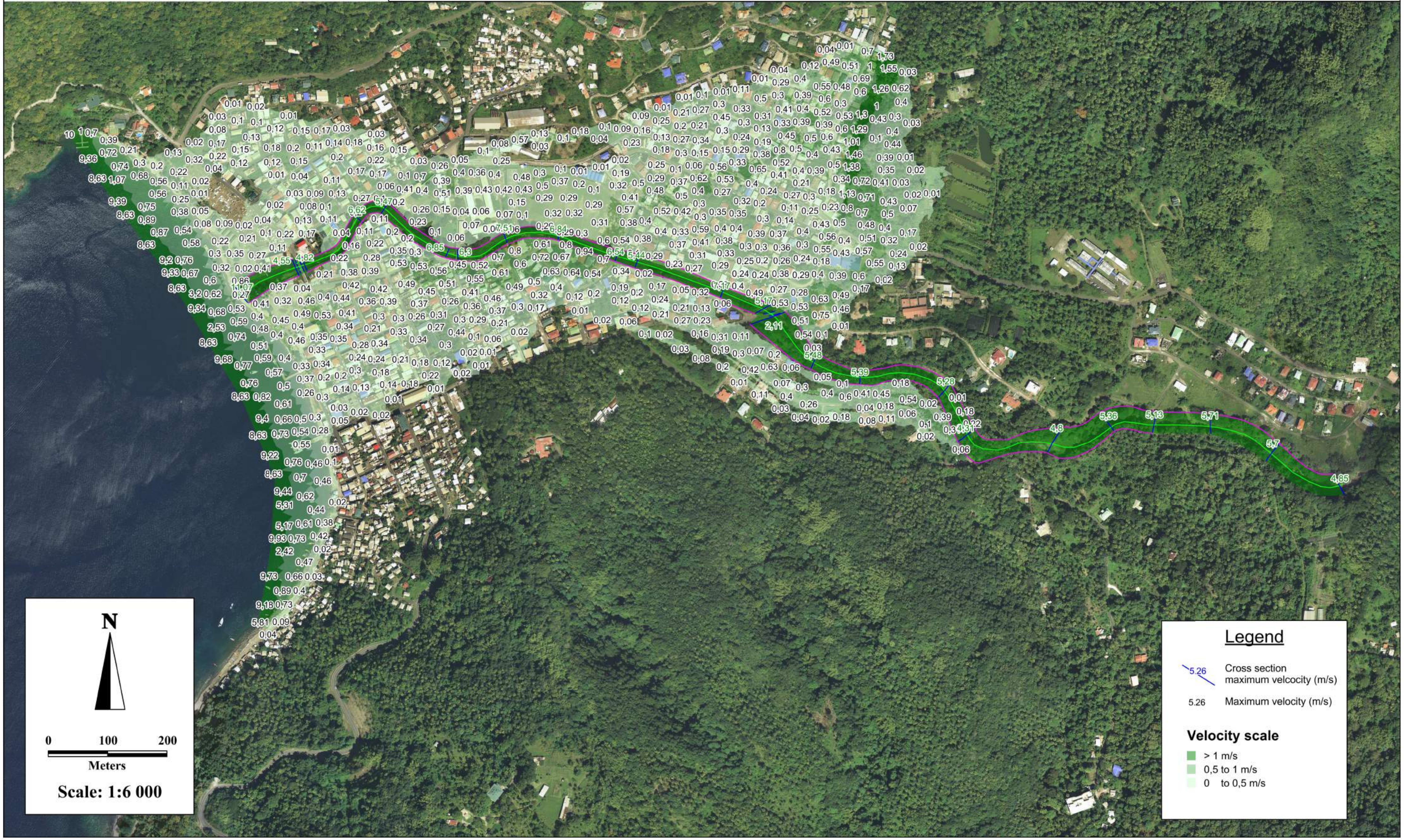
Flood exposure map
Velocity for 1-in-50 year flood event



V1_May-14

Hydraulic assessment for flood risk assessment in Soufriere, Fond St Jacques and Dennery

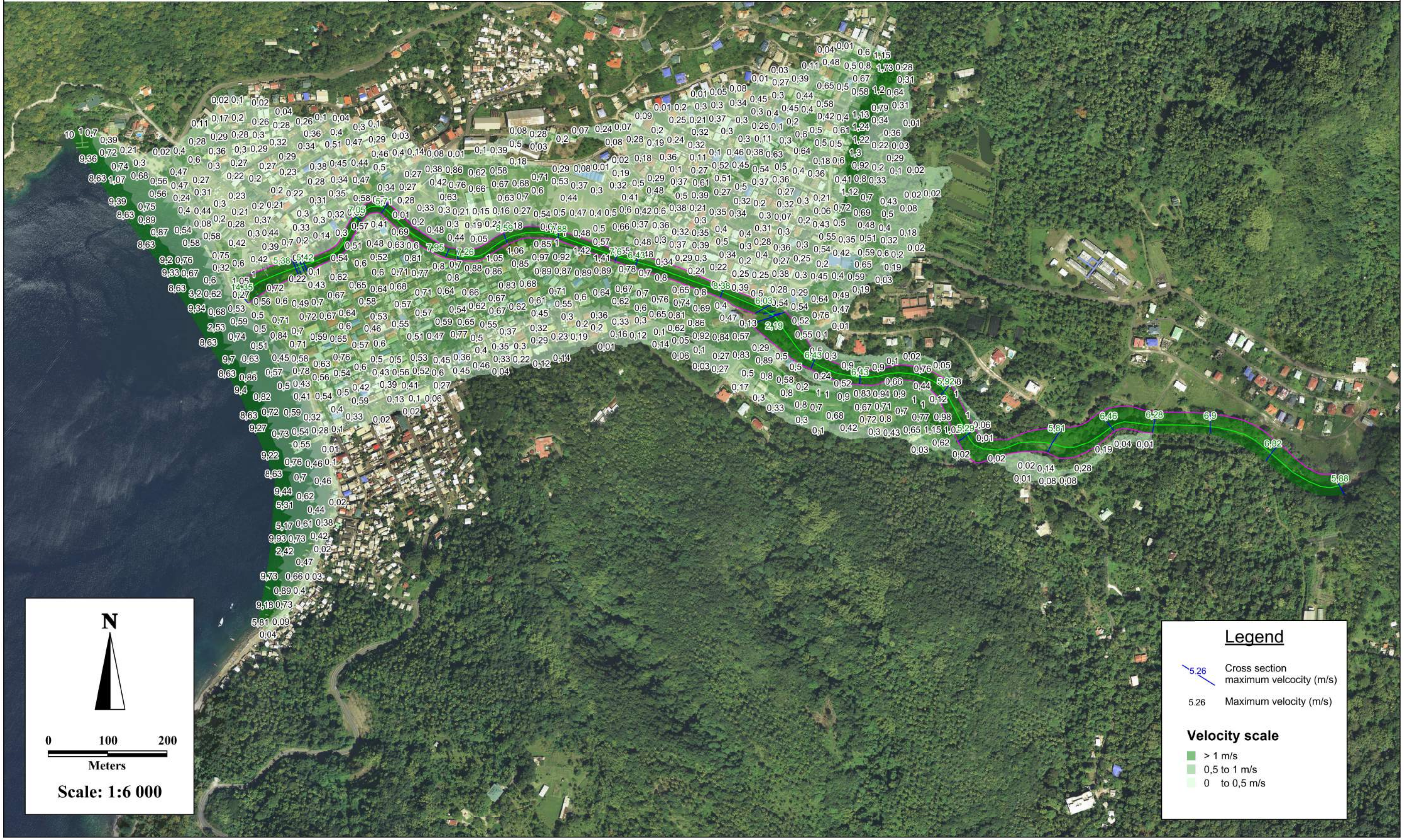
Flood exposure map
Velocity for 1-in-100 year flood event



V1_May-14

Hydraulic assessment for flood risk assessment in Soufriere, Fond St Jacques and Dennery

Flood exposure map
Velocity for Tomas event



V1_May-14

Hydraulic assessment for flood risk assessment in Soufriere, Fond St Jacques and Dennery

Flood exposure map
Water levels for 1-in-10 year flood event

V1_May-14

Hydraulic assessment for flood risk assessment in Soufriere, Fond St Jacques and Dennery

Flood exposure map
Water levels for 1-in-50 year flood event

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V1_May-14

Hydraulic assessment for flood risk assessment in Soufriere, Fond St Jacques and Dennery

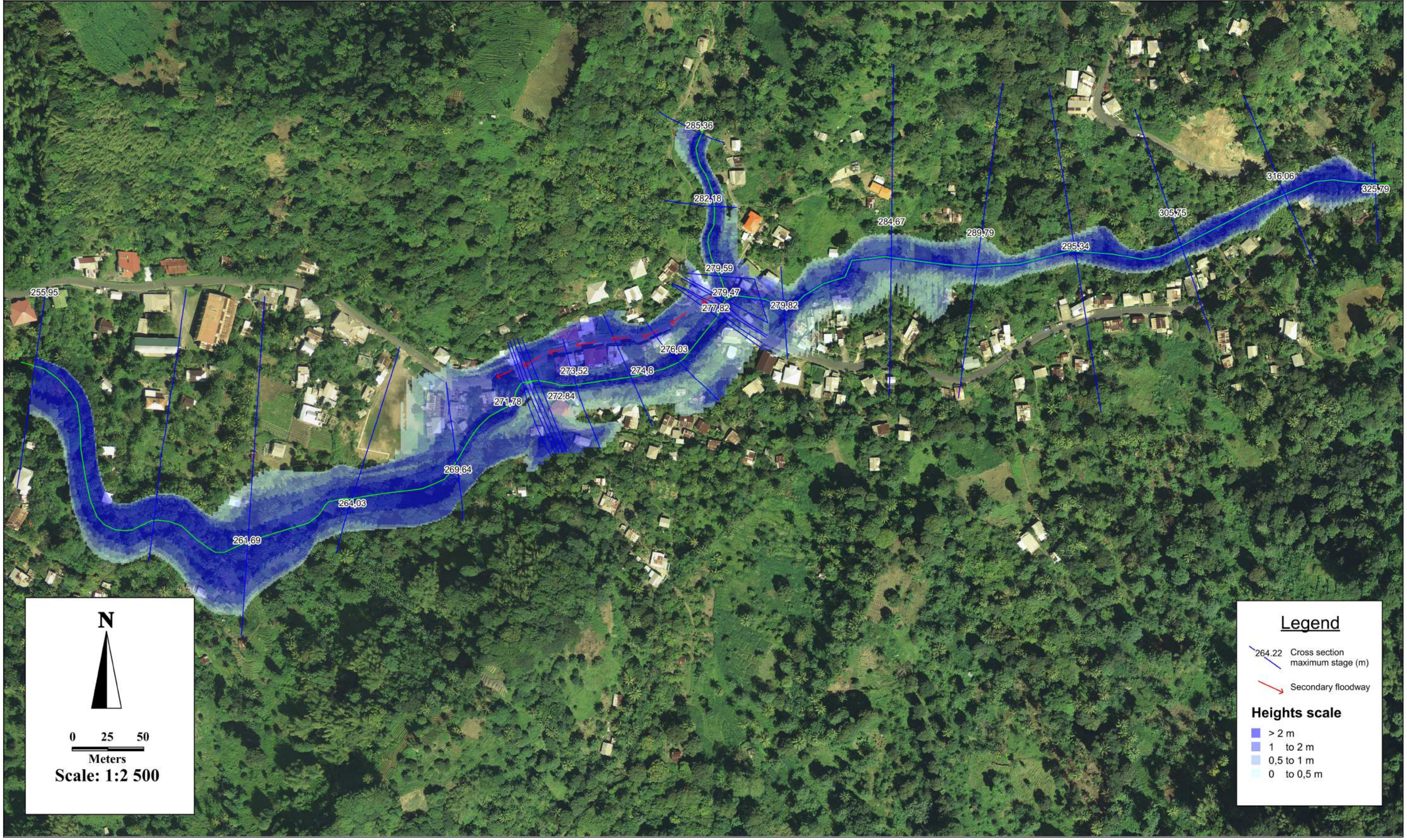
Flood exposure map
Water levels for 1-in-100 year flood event

egis

V1_May-14

Hydraulic assessment for flood risk assessment in Soufriere, Fond St Jacques and Dennery

Flood exposure map
Water levels for Tomas event



V1_May-14

Hydraulic assessment for flood risk assessment in Soufriere, Fond St Jacques and Dennery

Flood exposure map
Velocity for 1-in-10 year flood event

V1_May-14

Hydraulic assessment for flood risk assessment in Soufriere, Fond St Jacques and Dennery

Flood exposure map
Velocity for 1-in-50 year flood event

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V1_May-14

Hydraulic assessment for flood risk assessment in Soufriere, Fond St Jacques and Dennery

Flood exposure map
Velocity for 1-in-100 year flood event

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Flood exposure map
Velocity for Tomas event

Scale: 1:2 500

Legend

3.62 Cross section maximum velocity (m/s)

Velocity scale

🟩 > 1 m/s
🟩 0,5 to 1 m/s
⬜ 0 to 0,5 m/s

- Études générales
- Assistance au Maître d’Ouvrage
- Maîtrise d’œuvre conception
- Maîtrise d’œuvre travaux
- Formation

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